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Assessment of Physical Coal Cleaning Practices for Sulfur Removal

Science Applications International Corp., Norristown, PA

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

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ASSESSMENT OF
PHYSICAL COAL CLEANING
PRACTICES FOR
SULFUR REMOVAL

Prepared for

Office of Air and Radiation

Prepared by

Air and Energy Engineering Research
Laboratory
Research Triangle Park NC 27711

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Assessment of Physical Coal Cleaning Practices for Sulfur Removal

Final Report

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Abstract

This report presents results of a study of the current level of coal cleaning activity in the United States. In 1983, the U.S. Department of Energy's Energy Information Administration (EIA) expanded coal data collection activities to include information on the extent and type of coal preparation conducted in each coal-producing region. The additional information included data on raw coal input to coal cleaning plants, clean coal output, quality characteristics of the prepared coal, and end-use markets of both raw and prepared coal. These data, in combination with other EIA data, provide information on the extent and type of coal cleaning activity in each major coal-producing state or region. The impact on coal preparation of differences in mining methods and requirements of the various end-use markets also is discussed. Estimates were developed of SO₂ emission reduction by current mechanical cleaning plants based on clean coal quality characteristics reported to EIA and bed/county raw coal quality estimated from the EIA/U.S. Bureau of Mines (USBM) analytical file. Estimates also were developed of the potential for improving current SO₂ reduction levels through additional cleaning and the costs associated with each level of SO₂ reduction. The current level of SO₂ reduction by mechanical cleaning is estimated at about 5 million metric tons per year. An estimated 2 million to 3 million metric tons of additional emission reduction could be achieved through additional coal cleaning activity, at an average cost of about \$150 to \$200 per ton of SO₂.

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Executive Summary

Coal preparation removes ash, sulfur, moisture, and other impurities from raw coal. Coal preparation processes vary among regions because mining methods, geological conditions, and end-use market requirements differ by geographic area. In this study, the extent to which coal producers in different regions of the United States currently clean their coal was estimated and the potential SO₂ reduction that can be achieved through increased cleaning was determined. Estimates of the potential for increasing SO₂ reduction were derived on the basis of a consideration of commercially-proven, conventional cleaning technology (i.e., physical coal cleaning) *only*; chemical coal cleaning is not considered in this study.

Coal Preparation Techniques

All coal, including the final product shipped to end-use markets, contains impurities. Some impurities are introduced from the area around the coal seam during extraction; others are within the seam itself. The raw coal's physical characteristics, and the intensity of the preparation it undergoes, determine the quality of the final product. The two basic cleaning procedures used in preparation plants are crushing and screening, and mechanical cleaning ("washing").

The simplest cleaning procedure is crushing and screening. In crushing and screening, the raw coal is pulverized into fragments small enough to pass through a screen, separating the coal from the harder non-coal rock particles that are more difficult to crush. Crushing and screening, however, tends not to remove the smaller foreign particles or impurities within the coal seam. Smaller particles and internal impurities respond only to mechanical cleaning, a more expensive and involved process that begins with crushing and screening and ends with separation and dewatering. Separation uses the specific gravity differences between coal and other particles to filter out impurities. However, coal is filtered out along with the impurities during mechanical cleaning. As the amount of refuse material removed approaches 100 percent, the amount of coal lost increases and mechanical cleaning becomes economically unattractive beyond a certain level of purity. Thus, the decision to mechanically clean (as opposed to simply crushing and screening) involves an economic trade-off between the quality and the quantity of the end product.

Typically, preparation plants are classified according to four preparation levels; this same classification scheme has been used throughout this report. Preparation level 1 consists of crushing and screening only. Preparation level 2 uses a single mechanical cleaning circuit, designed to clean the coarse fraction of the raw input stream. (The other size fractions may or may not be passed through the circuit). Preparation level 3 consists of two separate mechanical cleaning circuits, one for coarse and one for mid-sized coal. (The fine-sized coal may or may not be passed through the mid-sized circuit.) Finally, in preparation level 4, three (sometimes four) mechanical cleaning circuits are used -- one for coarse, one for mid-sized, and one for fine coal.

Data Sources

The results of this study for current coal preparation activities are based primarily on analysis of data derived from two Energy Information Administration (EIA) survey forms: the 1983 EIA-7A

and the 1983 EIA-7A (Supplement) "Coal Production Report." The EIA-7A forms are sent annually to mines that produce, process, or prepare 9,070 or more metric tons (10,000 or more short tons) of coal per year. The EIA-7A form requests data on the:

- Type of mining operation (underground, surface, preparation plant, etc.).
- Production by coal bed and coal rank.
- Breakdown of production by market type (captive, openstocks, etc.) and the value free-on-board (FOB) mine.
- Respective percentages of prepared coal (for mines that include preparation plants) from surface and from underground mines.

The EIA-7A Supplement is a biennial survey of coal mines that produce, process, and prepare 90,700 or more metric tons (100,000 or more short tons) per year. The EIA-7A Supplement form requests data on:

- Tonnage shipped without preparation.
- Tonnage crushed and screened only.
- Tonnage mechanically cleaned.
- Tonnage shipped to each end-use market (electric utilities, coke plants, exports, etc.).

Information from each form is combined to produce the EIA-7A coal data base, a computer file maintained and updated annually by EIA.

Coal data also are available from the Federal Energy Regulatory Commission (FERC) Form 423 computer file (maintained by EIA), "Cost and Quality of Fuels for Electric Utility Plants." The file includes information on the quality of coal delivered to electric powerplants and, for most plants, the name(s) and location(s) of the mine(s) from which they purchased the coal. The U.S. Bureau of Mines/EIA analytical computer file (also maintained by EIA) supplements the EIA-7A and FERC-423 forms by providing information on raw coal quality by seam and county for each producing state.

The conclusions drawn in this report concerning the potential SO₂ reduction from additional preparation of both the cleaned and uncleaned portions of current production are based on an extensive analysis of currently available data on coal washability and demonstrated coal reserves. The coal washability data were obtained from the U.S. Department of Energy's washability data base* and several U.S. Bureau of Mines Reports of Investigation.¹ These data were combined into a single data base representing the major producing coal seams in the United States.

* This data base was originally developed by the U.S. Bureau of Mines, but is now maintained and updated by the U.S. Department of Energy's Pittsburgh Energy Technology Center. The data base is available on computer tape.

The 1971 U.S. Demonstrated Coal Reserve Base (DRB) (maintained as a computer file by EIA) was the principal source of information on coal reserves at the bed/county level. This data base is the only source of coal reserve data disaggregated by coal seam (bed) and location (county). However, because substantial changes in quantities have been assigned to the DRB since 1971, it was necessary to adjust the 1971 figures to reflect the most recent updates. The updating was accomplished using the 1983 DRB² (containing reserves only at the state level) together with the more disaggregated data base to derive the best possible estimates of reserves by bed and county. (Chapter 4 discusses in detail the development of the revised bed/county data base).

After the demonstrated coal reserves were distributed by bed and county, the reserves were disaggregated further by quality within each bed/county combination. This was accomplished using a coal quality data base assembled from the Bureau of Mines/EIA analytical file and other sources. Overall, more than 33,000 coal quality samples were obtained and merged into the new reserve data base. The result was a set of data that identified both coal quantity and quality at the lowest possible level of aggregation.

The study divides the United States into five coal-producing regions: Central Appalachia, Southern Appalachia, Northern Appalachia, the Midwest, and the West. The division was made to capture existing differences in mining methods, geologic conditions, in-seam coal quality, and end-use markets -- factors that affect the type and degree of coal-cleaning activities.

Regional Analysis

In 1983, over 50 percent of U.S. raw coal production was cleaned. Seventy percent of underground coal production was mechanically cleaned, and 23 percent of surface coal production was mechanically cleaned.

The high percentage of underground-mined coal mechanically cleaned can be attributed to the fact that virtually all production of metallurgical-grade coal comes from underground mines. Also, more use of highly mechanized mining techniques, such as continuous and longwall mining, has reduced the average particle size of the run-of-mine product, thereby making the output less responsive to crushing and screening alone. Lastly, increased emphasis on quality on the part of end-users has had a direct impact on the amount of coal being mechanically cleaned.

Central Appalachia

The Central Appalachia region consists of eastern Kentucky, Tennessee, Virginia, and West Virginia. In 1983, Central Appalachian mining operators mechanically cleaned 73 percent of their production and crushed and screened an additional 20 percent. As is the case for the nation as a whole, the use of mechanical cleaning in Central Appalachia is highly correlated with mining method. For the region as a whole, over 96 percent of the more than 100 million metric tons (110 million short tons) of raw coal output from underground mines was at least crushed and screened before being sold. However, 21 percent of surface production, 7.6 million metric tons (8.4 million short tons), was sold without any form of preparation. Virtually all of the "no-preparation" coal was sold to electric utilities.

Nonetheless, mechanical cleaning is important in Central Appalachia; the region contains 158 mechanical cleaning plants, more than half the U.S. total. During the period of study (1983), Central Appalachia sold most of its output to domestic electric utility companies. The second leading customer was the export market, both in terms of metallurgical- and steam-grade products.

Some 88 of Central Appalachia's mechanical cleaning plants are in West Virginia; more of that state's output is mechanically cleaned than that of any other Central Appalachian state except Tennessee (by volume a relatively minor coal producer) (Table ES-1). This reflects West Virginia's importance as a source of metallurgical coal for both foreign and domestic use.

Data for 1983 show that plants in Central Appalachia prepared 146.6 million metric tons (161.2 million short tons) of their 200.9 million metric tons (221.5 million short tons) of coal. The region's mechanical cleaning plants showed an overall clean-coal yield (salable product as a percentage of input to preparation plants) of 64 percent. The clean coal yield for individual Central Appalachian states are as follows: eastern Kentucky, 62 percent; Tennessee, 57 percent; Virginia, 59 percent; and West Virginia, 65 percent.

Southern Appalachia

The Southern Appalachia region consists of Alabama and Georgia; however, since Georgia is not a major coal producer, data are available only for Alabama. The state's coal, 79 percent of which was mechanically cleaned, is relatively low in sulfur. Alabama contains about 30 mechanical cleaning plants that have stepped up coal preparation considerably in recent years. Of the 20.8 million metric tons (22.9 million short tons) of raw input to preparation plants, the final salable yield was 65 percent, or 13.6 million metric tons (15 million short tons). Like those in Central Appalachia, Alabama plants sold most of their coal to the domestic utility industry, and mechanically cleaned most of that coal.

Table ES-1. Central Appalachian Coal Preparation (1983)^a

Area	Quantity Produced (Million Raw Metric Tons)	Percentage Mechanically Cleaned	Percentage Crushed and Screened	Percentage Not Prepared
Eastern Kentucky	50.7	57	27	16
Tennessee	4.2	80	20	0
Virginia	25.0	77	16	7
West Virginia	121.0	79	19	2
<i>Total</i>	<i>200.9</i>	<i>74</i>	<i>20</i>	<i>6</i>

^aAll values include only mines producing more than 90,700 metric (100,000 short) tons of coal per year and reporting on Form EIA-7A Supplement.

Northern Appalachia

The Northern Appalachia region consists of Pennsylvania, Ohio, and Maryland. The plants in the region mechanically cleaned 70 percent of the region's coal and crushed and screened 22 percent (Table ES-2). In 1983, the region contained over 85 mechanical cleaning plants, about 20 percent of the U.S. total. As the largest coal producer in the region and the only state with any significant metallurgical coal reserves, Pennsylvania contains most of these plants.

Plants in Ohio, however, have dramatically increased mechanical cleaning in recent years (from 47 percent in 1978 to 82 percent of total production in 1983) so that Ohio coal, relatively high in impurities, can compete in today's quality-conscious market. Although more Ohio coal is washed now, a third of Ohio's mechanical cleaning plants are single-circuit; that is, coal fed into the plants undergoes the lowest level of mechanical preparation.

(The highest number of cleaning circuits in mechanical cleaning plants currently in operation is four circuits.)

Clean-coal yields in Northern Appalachia exceed considerably those in Central Appalachia. The difference in yields for the two regions partly reflects the fact that Northern Appalachia coal seams tend to be thicker (1.63 meters versus 1.37 meters based on 1983 EIA-7A data), thus reducing the amount of dilution material added to the coal during the mining process. Also, much of the coal cleaning in Central Appalachia is for metallurgical purposes, and thus entails a generally more intensive process than the preparation of steam coal. Preparation reduced the region's total output from 103 million metric tons (113.5 million short tons) to 82.9 million metric tons (91.4 million short tons), a loss of about 20 percent. Yields from mechanical cleaning were 76 percent, 70 percent, and 71 percent for Maryland, Ohio, and Pennsylvania, respectively.

The Midwest

Illinois, Indiana, and western Kentucky constitute the Midwest region. Some 95 percent of the region's coal was either mechanically cleaned or crushed and screened (Table ES-3). Illinois

Table ES-2. Northern Appalachian Coal Preparation (1983)^a

Area	Quantity Produced (Million Raw Metric Tons)	Percentage Mechanically Cleaned	Percentage Crushed and Screened	Percentage Not Prepared
Maryland	5.39	58	26	16
Ohio	33.39	82	14	4
Pennsylvania	64.35	65	25	10
<i>Total</i>	<i>103.13</i>	<i>70</i>	<i>22</i>	<i>8</i>

^aAll values include only mines producing more than 90,700 metric (100,000 short) tons of coal per year and reporting on Form EIA-7A Supplement.

Table ES-3. Midwestern Coal Preparation (1983)^a

Area	Quantity Produced (Million Raw Metric Tons)	Percentage Mechanically Cleaned	Percentage Crushed and Screened	Percentage Not Prepared
Illinois	63.0	93	6	1
Indiana	33.7	78	17	5
Western Kentucky	36.5	72	18	10
<i>Total</i>	<i>133.2</i>	<i>83</i>	<i>12</i>	<i>5</i>

^aAll values include only mines producing more than 90,700 metric (100,000 short) tons of coal per year and reporting on Form EIA-7A Supplement.

producers mechanically clean about 93 percent of their raw coal output, and Indiana, whose coal is almost all surface-mined, mechanically cleans over 70 percent of its coal. Preparation reduced the region's 133 million metric tons (146.6 million short tons) of raw coal to 104 million metric tons (114.6 million raw tons). The Midwest's overall mechanical cleaning yield was 74 percent, significantly higher than yields for the coal-producing areas of Appalachia (64 percent, 65 percent, and 70 percent for Central, Southern, and Northern Appalachia, respectively). Much of this difference can be attributed to the fact that very little metallurgical coal is mined and prepared in the Midwest. Yield figures for Midwestern preparation plants, therefore, do not reflect the cleaning losses associated with the intense preparation of this product type.

As indicated above, most of the production from this region is sold as a steam product to electric utilities. In Illinois and Indiana, 86 percent of the total salable output was sent to the utility market. In western Kentucky, 92 percent of production went to electric utilities. Of this production, 91 percent, 72 percent, and 65 percent was mechanically cleaned for Illinois, Indiana, and western Kentucky, respectively. These percentages reflect differences in in-place reserve quality as well as mining conditions and methods within each state.

The West

Coal washing in the Western coal-producing states, except for the interior states,* is not very extensive. The coal mined in this region is primarily a sub-bituminous product, none of which is mechanically cleaned. Bituminous coal, for use by electric utilities, is mined in Colorado, Utah, and, to a much lesser extent, New Mexico. Utility coal mined in these states is inherently high Btu, low-sulfur, and low-ash and does not require extensive cleaning. Only 6 percent of the utility coal mined in Colorado in 1983 was mechanically cleaned. In Utah, the figure was about 13 percent of utility coal production, and in New Mexico, less than 1 percent of the bituminous steam coal was cleaned. In contrast, Missouri produces bituminous coal exclusively, and the utility coal

* The interior states are Arkansas, Iowa, Kansas, Missouri, and Oklahoma.

mined in the state is high in sulfur. Approximately 51 percent of Missouri's utility coal production was cleaned in 1983. Although very little coal produced in the West is mechanically cleaned, over 80 percent of all production (both bituminous and sub-bituminous) is crushed and screened.

Current SO₂ Reduction

The method used to determine current SO₂ reduction levels was structured to take advantage of the 1983 EIA-7A Supplement data. In addition to providing information on the quantity of coal mechanically cleaned, this data base also includes quality information on coal shipped to each end-use sector. By obtaining raw sulfur inputs on a bed/county basis from the EIA/USBM analytical file, estimates of SO₂ reduction obtained through mechanical cleaning could be derived.

The use of the average bed/county SO₂ content as a proxy for the actual SO₂ content of the raw feed* to the plant is the primary cause of uncertainty in the estimation procedure. The data used represent information on coal in place and coal being mined at the time the samples are taken. This could result in an estimate at the bed/county level substantially different from the coal currently mined. Consequently, any inferences drawn from the analysis must be viewed against the potential uncertainty caused by inherent limitations of the raw data.

The problem of uncertainty is addressed separately from the analysis. A method was developed whereby estimates of uncertainty at different levels in the analysis could be combined meaningfully to develop an overall estimate of the probable error. The uncertainty analysis is discussed in more detail in Chapter 1 and Appendix B.

The procedure used to develop the SO₂ reduction estimates is described in the main body of this report. Table ES-4 presents the results obtained through the application of the procedure.** As the data indicate, Appalachian operators cleaned more coal than their Midwestern and Western counterparts combined; of a total of approximately 245 million metric tons (270 million short tons) of as-shipped coal produced by Appalachian operations in 1983, approximately 156 million metric tons (172 million short tons), or 64 percent, was mechanically cleaned. The coal that was

* That is, the SO₂ equivalent of the sulfur content of the raw feed, assuming that *all* of the sulfur in the feed would be released as SO₂ upon consumption. The convention of referring to the SO₂ equivalent of the sulfur content of coal as the "SO₂ content" of the coal has been adopted herein for convenience. Unless otherwise noted, all estimates of the SO₂ content of coal are based on the assumption that *all* of the sulfur in the coal would be released as SO₂.

** Results for Maryland are not included in this table. In 1983, only one cleaning plant was operating in Maryland, and data for this plant were not usable.

Table ES-4. Current SO₂ Reduction Estimates (Based on 1983 Data)

Region and State	Quantity of Coal Cleaned ^a (Thousand Clean Metric Tons)	Quantity of SO ₂ in Raw Coal ^a (Thousand Metric Tons)		
		Input to Mechanical Cleaning Plants	Removed Through Mechanical Cleaning	Remaining in Clean Coal
Appalachia ^b				
Alabama	13,377	397	55	342
Eastern Kentucky	18,067	431	159	272
Ohio	19,317	2,175	741	1,434
Pennsylvania	29,689	1,838	827	1,011
Tennessee	1,919	81	58	23
Virginia	11,186	243	45	198
West Virginia	62,745	2,875	943	1,932
Total	156,300	8,040	2,828	5,212
Midwest				
Illinois	43,448	3,877	1,463	2,414
Indiana	19,588	1,466	204	1,262
Western Kentucky	19,599	2,163	848	1,315
Total	82,635	7,506	2,515	4,991
West				
Colorado	1,434	27	10	17
Missouri	2,362	363	130	233
New Mexico	145	3	1	2
Utah	1,367	24	12	13
Total	5,308	417	153	265
Grand Total	244,243	15,963	5,486	10,468

^aIncludes only coal produced and SO₂ removed by operators that mined over 90,700 metric (100,000 short) tons in 1983.

^bMaryland results not included (see text).

processed by the region's plants contained a total of 8.0 million metric tons (8.8 million short tons) of SO₂; of this total, 2.9 million metric tons (3.2 million short tons) (36 percent) was removed from the coal through cleaning. Nearly all of this 2.9 million metric tons (3.2 million short tons) of SO₂ was removed from coal that was mined and processed in the northern part of the region (i.e., Pennsylvania, Ohio, and West Virginia); in fact, Northern Appalachian plants accounted for 88 percent of the total SO₂ reduction. This is in part a reflection of the fact that Northern Appalachian coal is generally higher in sulfur content than is the coal in Southern Appalachian reserves; more SO₂ can be removed from Northern Appalachian coal because more SO₂ is present in the coal. In fact, more SO₂ was removed from Ohio, Pennsylvania, and West Virginia coal than was present in the raw coal processed by Southern Appalachian operators.

In Northern Appalachian states (particularly Pennsylvania), good SO₂ reduction results are being achieved through cleaning; thus, Northern Appalachia may represent an area in which increased mechanical cleaning could significantly increase the SO₂ removed.* In general, the same is not the case for Central and Southern Appalachia because the sulfur content of Central and Southern Appalachian coal is quite low; at least in Virginia and Alabama, the coal is not amenable to sulfur reduction through washing. Within Southern Appalachia, only the unwashed coal of eastern Kentucky contains a relatively large quantity of SO₂ that is potentially removable through cleaning.

Although Midwestern operators cleaned less coal than those in Appalachia in absolute terms (82.5 million clean metric tons (90.0 million short tons) versus 156 million metric tons (172 million short tons) for Appalachia), in relative terms, it cleaned a larger percentage of its as-shipped production (76 percent, versus 64 percent for Appalachia). The coal that was processed by the region's plants contained 7.5 million metric tons (8.3 million short tons) of SO₂; of this total, 2.5 million metric tons (2.8 million short tons), or about 34 percent, was removed through cleaning. These sulfur and sulfur-reduction quantities are not much lower than the corresponding quantities for Appalachia, despite the fact that in Appalachia nearly twice as much coal was cleaned as in the Midwest. This is indicative of the fact that Midwestern coal is much higher in sulfur than Appalachian coal, a situation that has clearly forced Midwestern operators to rely more heavily on mechanical cleaning than do their Appalachian counterparts. In fact, of operators in all the mining regions, only those in the Midwest are cleaning as large a percentage of their surface production as their underground production; thus, it appears that sulfur, rather than ash, reduction may be the primary objective of Midwestern preparation plant operators.

In addition to presenting SO₂ reduction estimates for the major Appalachian and Midwestern coal-producing states, Table ES-4 also provides estimates for those Western states for which usable EIA-7A data were available. Four Western states are included in the table; one of these is characterized by high-sulfur reserves (Missouri), and three are characterized by low-sulfur coal (Colorado, New Mexico, and Utah). Because of the low absolute tonnage of bituminous coal

* It should be noted that, throughout this report, coal cleaning is considered in isolation from other SO₂ reduction technologies, such as flue gas desulfurization. Therefore, the statement that significant increases in SO₂ reduction can be achieved by cleaning Northern Appalachian coal is based on the assumption that *no* SO₂ is currently being removed from this coal by other means.

production and/or processing conducted in these states, relatively little SO₂ reduction is achieved through coal cleaning.

Potential Reductions

The method used to determine potential SO₂ reduction from physical coal cleaning is based on the assignment of average washability characteristics to coal reserves on a bed/county basis. This approach was taken because it allows the calculation of a range of SO₂ reduction estimates for various coal preparation options. Within each option (corresponding to a given level of preparation), separation gravities could be chosen so as to yield optimum SO₂ reduction levels for preselected, economically acceptable heat content yields (95 percent, 90 percent, etc.). Thus for each preparation option, a range of SO₂ reduction estimates corresponding to selected heat content yield values could be developed.

To implement this methodology, a considerable amount of effort was expended to identify and gather available data on coal washability and to construct a data base that could be mapped against demonstrated coal reserves, providing an enumeration, as complete as possible, at the bed/county level. The data sources used to complete this task were discussed above.

Another critical component of this effort was the selection of a model to assist in determining SO₂ reduction and costs associated with preparation options. For the purposes of this project the Skea and Rubin coal preparation model was chosen as the basic analysis tool. While the basic framework of the model was left intact, several modifications were made to the costing algorithms and other components to fit the specific needs of this study.

Overall, considerable work was expended to come up with potential SO₂ reduction estimates and costs for both the cleaned and uncleaned portions of current production. Because of the detail and complexity of the methodology, a lengthy discussion of the approach is provided in Chapter 4.

As discussed above, the first step in the process was to develop a coal reserve base by bed/county, which contained corresponding average washability data. Using this reserve base, washability curves were prepared for both the cleaned and uncleaned portions of each region's current production. These curves show the SO₂ reduction potential by preparation option and heat content yield, as well as the corresponding cleaning costs in dollars per metric ton (in parentheses). Examples of the curves are shown by Figures ES-1 and ES-2.

Using these figures and information on the coal preparation and mining industries within each region, a range of SO₂ reductions and corresponding costs was developed using "light" and "heavy" coal cleaning scenarios.

Each cleaning scenario is defined by a preparation level and a heat content yield. In defining the scenarios, economic as well as technical considerations were taken into account. The definition of light and heavy cleaning thus varies from state to state, reflecting regional variability in the washability of coal. Also, the scenario definitions vary within each state for the cleaned and uncleaned portion of the state's production. In the case of the cleaned production, both the light and the heavy cleaning options represent additional or more intensive cleaning, over and above the cleaning to which the coal has already been subjected. Mine operators already cleaning their coal can attain highly intensive levels of cleaning at a lower additional cost than other operators,

Figure ES-1. Clean Coal Content Versus Heat Content Yield and Preparation Costs for Illinois' 1983 Uncleaned Production

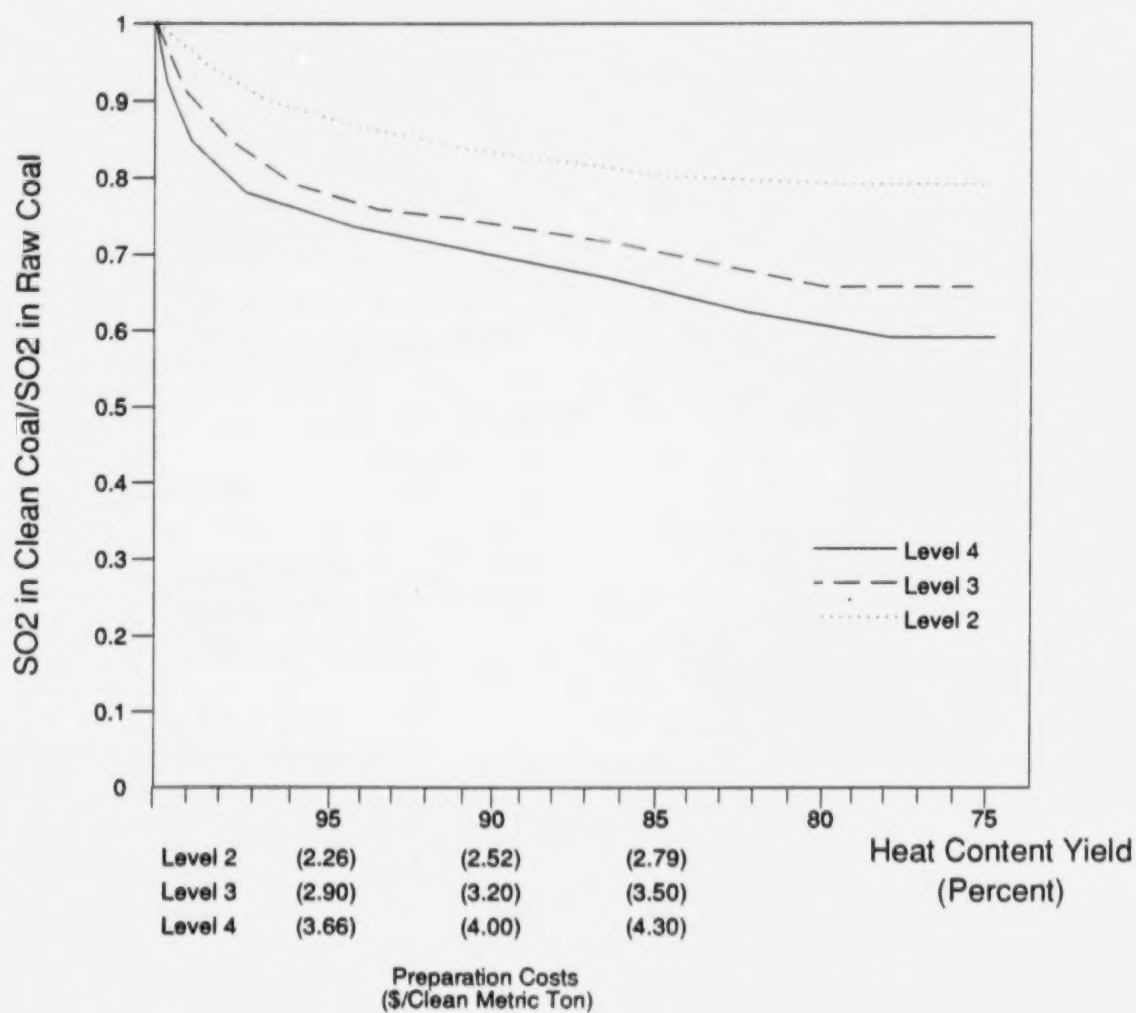
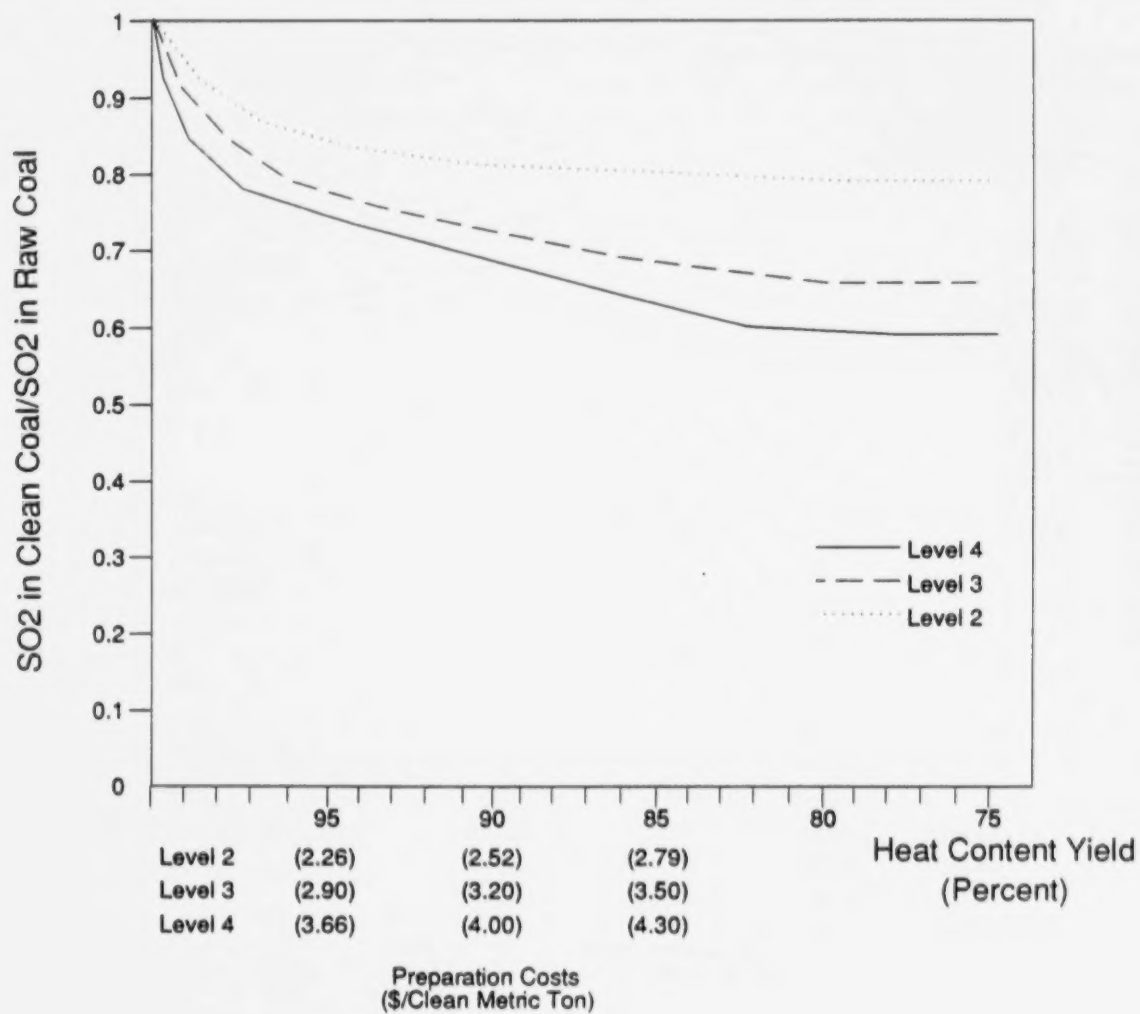


Figure ES-2. Clean Coal Content Versus Heat Content Yield and Preparation Costs for Illinois' Clean Production



simply by expanding their existing cleaning plants and/or modifying the plants' operating characteristics. For this reason, the definitions of light and heavy cleaning reflect a more intensive degree of preparation than in the case of the uncleaned coal. Significant additional SO₂ reduction through further cleaning of the uncleaned production, beyond heavy cleaning, is thus technically feasible in many states, although the resulting costs would be high if not prohibitive. The definitions of the cleaning scenarios within each state are presented in Table ES-5.

Using available information, it was estimated that approximately 19 million metric tons (21 million short tons) of SO₂ is contained in the raw coal mined in the coal-producing states east of the Mississippi River. These states contain the majority of bituminous coal reserves that traditionally are cleaned. It is estimated that slightly over 5 million metric tons (5.5 million short tons) of SO₂ currently is being removed by existing coal preparation plants and cleaning procedures. Under a "light cleaning" scenario in which all production is subjected to some form of moderate preparation, an additional 1.7 million metric tons (1.9 million short tons) of SO₂ can be removed. A "heavy cleaning" of all production results in an additional 3.1 million metric tons (3.4 million short tons) of SO₂ being removed.

In addition to the quantity of SO₂ that can be removed via coal cleaning, a corresponding cost was calculated. The model estimates the capital and operating costs (in 1986 dollars) of the cleaning process using equations that relate costs to the clean plant output (in tons/hour), weight yield, and other relevant operating and financial parameters. The economic assumptions used in developing the cost estimates are shown in Table ES-6. It should be stressed that the cost estimates include only the costs of the cleaning process itself; neither the *reductions* in coal transportation and power plant operating costs resulting from cleaning, nor the value of the coal lost to the refuse, are included in the estimates. Under the light cleaning scenario the estimated cost for the East as a whole is about \$206 per metric ton (\$187 per short ton) of SO₂ removal. The cost for heavy cleaning is about \$151 per metric ton (\$137 per short ton). These figures do not necessarily suggest that heavy cleaning is always the best option. The "best" level of cleaning can only be determined by corresponding examinations of costs on a dollar per ton of coal cleaned basis and heat content losses. However, the results of this study do suggest that substantial amounts of SO₂ can be removed through coal cleaning at costs that appear to be less than current post-combustion technologies. Table ES-7 provides a summary of the current and potential SO₂ reduction estimates developed during this study.

Recommendations

The principal output of this effort is a comprehensive data base that characterizes U.S. coal reserves by their sulfur reduction potential through physical coal cleaning. For the first time, data on the quantity, quality, washability, and minability of coal reserves on a bed/county basis have been combined into a single comprehensive data base. There are many possible applications of the data base. For example, the data base may be linked with a policy model such as the Advanced Utility Simulation Model to enhance the model's current capabilities by providing a detailed structural representation of coal preparation. With this representation in place, more accurate and defensible analyses of the tradeoffs among control technologies can be developed.

A second application of the data base is the direct analysis of specific target areas. The current study was limited to the development of SO₂ reduction estimates at the regional and national

Table ES-5. Definitions of Cleaning Scenarios

Area/State ^a	Light Cleaning		Heavy Cleaning	
	Preparation Level	Heat Content Yield	Preparation Level	Heat Content Yield
West Virginia				
Uncleaned	3	95	3	90
Cleaned	4	88	4	85
Eastern Kentucky				
Uncleaned	2	95	2	90
Cleaned	4	89	4	86
Virginia				
Uncleaned	2 ^b	97	3 ^b	96
Cleaned	N/A ^b	N/A ^b	N/A ^b	N/A ^b
Alabama				
Uncleaned	2	95	3	85
Cleaned	4	90	4	85
Pennsylvania				
Uncleaned	3	95	4	90
Cleaned	N/A ^c	N/A ^c	4	85
Ohio				
Uncleaned	2	95	3	90
Cleaned	4	89	4	85
Illinois				
Uncleaned	2	95	3	90
Cleaned	4	90	4	85
Indiana				
Uncleaned	2	95	3	90
Cleaned	3	95	4	85
Western Kentucky				
Uncleaned	2	95	3	90
Cleaned	4	87	4	85

^aThe analysis of the potential for removing SO₂ through cleaning was limited to major coal-producing states east of the Mississippi River. The available data for major coal-producing states are too limited to support the development of SO₂ reduction estimates, and SO₂ reduction is not a major concern for western coal (which is already low in SO₂).

^bN/A = not applicable. The available washability data for Virginia are too limited to support the development of SO₂ reduction estimates for the state's cleaned production.

^cN/A = not applicable. Pennsylvania's cleaned production is already being subjected to an intensive degree of cleaning; therefore any additional cleaning must be heavy rather than light.

**Table ES-6. Economic Assumptions for All Model Runs
(Potential Reduction Scenarios)**

Annual Plant Operation	3325 hours per year
Plant Output	454 dry metric tons (500 dry tons) per hour
Economic life of plant	20 years
Nominal interest rate	10 percent
Rate of inflation	5 percent
Index updating 1978 base year costs to mid-1986 dollars (mid-1978 = 1)	1.484

**Table ES-7. Current and Potential SO₂ Reduction Estimates, and
Preparation Cost Estimates**

Region and State	Total 1983 Raw Production (Thousand Raw Metric Tons)	Total SO ₂ ^a in Raw Coal (Thousand Raw Metric Tons)	Quantity of SO ₂ (Thousand Metric Tons)			Preparation Costs (\$/ Ton SO ₂ Removal)	
			Currently ^b	Potentially Light ^c	Heavy ^c	Light	Heavy
Appalachia							
Alabama	26,300	766	55	80	182	309.06	180.47
E. Kentucky	50,700	1,209	159	145	240	306.17	238.84
Ohio	33,400	2,594	741	126	282	204.84	119.66
Pennsylvania	64,400	2,845	827	312	486	167.03	172.58
Virginia	25,000	386	45	16	21	464.91	455.13
W. Virginia	121,000	4,066	943	286	519	309.17	194.53
Total	320,800	11,866	2,770	965	1,730	251.71	183.99
Midwest							
Illinois	63,000	4,134	1,463	142	367	277.59	141.61
Indiana	33,700	1,986	204	322	610	74.48	84.76
W. Kentucky	36,500	2,967	848	229	385	151.23	114.96
Total	133,200	9,087	2,515	693	1,362	141.46	108.79
Grand Total^b	454,000	20,953	5,285	1,658	3,092	205.63	150.79

^aQuantity includes cleaned and uncleaned.

^bTennessee, Colorado, Missouri, New Mexico, Maryland, and Utah costs are not included here, because potential SO₂ reduction estimates were not developed for these states (see Table ES-5, especially footnote a.)

^cThe definitions of light and heavy cleaning vary by region, and are presented in Table ES-5.

levels. However, since the data are on a bed/county basis, many different levels of aggregation are possible. For example, one concern often raised when examining impacts of proposed acid rain legislation is what will be the effects on the mining regions of the Midwest. The data base can be used to focus on very specific areas and conduct detailed impact/tradeoff analyses. In Illinois one could look at the supply distribution pattern from the Herrin #5 and #6 seams; identify specific tonnages, coal quality, and delivered prices to utilities purchasing these coals; and then examine the specific washability of these coals and the costs associated with bringing them in-line with alternative control technologies.

A question often raised when examining coal supply issues is the quantity, availability and price of low-sulfur eastern bituminous coal. The answer to this question, for the most part, has been given in terms of in-place coal reserves' meeting specific pre-preparation quality characteristics. With the data base it is possible to identify the amount of coal that can be cleaned to a specified level, and the associated costs. Obviously, many similar questions can be addressed. The fact that the data base was constructed at the bed/county level makes it flexible and easy to use for addressing many varying coal supply/demand issues.

Some words of caution are in order. Throughout the course of this study every effort was made to obtain the most complete and reliable washability data available. To that end it is believed that the study was successful. However, while the data base was constructed on a bed/county basis, it does not cover all beds and all counties where mining is prevalent. Data gaps do exist, some more pronounced than others. The uncertainty in the estimates resulting from these data gaps is discussed in Chapter 1 and Appendix B.

Also, as discussed above, the definitions of light and heavy cleaning are based on economic as well as technical considerations, and reflect a less intensive degree of cleaning for the uncleaned portion of current production than for the cleaned portion.* Therefore, significant increases in SO₂ reduction, beyond those estimated for the heavy cleaning scenario, are technically feasible in some regions. Using the regional SO₂ reduction curves presented in Chapter 4, potential SO₂ reduction estimates can be obtained for any desired cleaning scenario (including scenarios reflecting more intensive degrees of cleaning than those defined as heavy cleaning in this report).

* The definitions of light and heavy cleaning for uncleaned coal were selected based on an analysis of the regional SO₂ reduction curves (see, for example, Figure ES-1), and do not necessarily correspond to current degrees of cleaning for cleaned coal.

1.

Introduction

Data Sources

The principal objectives of this study were to estimate SO₂ reductions resulting from mechanical cleaning activities in each of the coal-producing states, and to determine the amount of SO₂ reduction achievable through increased coal cleaning. Estimates of the potential for increasing SO₂ reduction were derived on the basis of a consideration of commercially-proven, conventional cleaning technology (i.e., physical coal cleaning) *only*; chemical coal cleaning was not considered in this study.

The information used to met the first objective came primarily from an Energy Information Administration (EIA) computerized data file containing 1983 data collected on Form EIA-7A and EIA-7A (Supplement) "Coal Production Report." The EIA-7A is an annual survey of mining operations that produce, process, or prepare 9,070 or more metric (10,000 or more short) tons of coal per year. Information collected by this survey includes:

- Type of mining operation; i.e., underground mine, surface mine, preparation plant, tippie, etc.
- Production by coal bed, and coal rank.
- Disposition of coal produced by market type (i.e., captive, open stocks) and the value free-on-board (FOB) mine.
- Percentages of prepared coal (for mining operations that include a preparation plant) originating from surface mines and from underground mines.

EIA-7A (Supplement), an addendum to EIA-7A, is sent to mining operations that produce, process, or prepare 90,700 or more metric (100,000, short) tons per year. The report is biennial, beginning in 1984 for the collection of 1983 data. In addition to the information collected by the EIA-7A, the Supplement provides specific data on coal preparation. These data include:

- Tonnage prepared by crushing and screening only.
- Tonnage loaded for shipment without processing.
- Tonnage mechanically cleaned by method:
 - wet methods (jigs, water cyclones, and concentrating tables),
 - dense medium processes (magnetite, sand, etc.),
 - froth flotation,
 - pneumatic methods.
- Tonnage shipped to each end-use market (i.e., electric utilities, coke plants, exports, etc.).

The second major EIA data system used in this study was the Federal Energy Regulatory Commission (FERC) Form 423 computer file (maintained by EIA), "Cost and Quality of Fuels for Electric Utility Plants," which provides plant-level information on the quality of coal delivered to electric utilities. The file also contains, for most power plants, the name and location of the mine(s) from which the coal was purchased. Using these data for the years 1980 through 1985, SAIC derived information the number of deliveries of mechanically cleaned steam coal to each state, the cleaning methods used for steam coal, and the characteristics of delivered steam coal.

The EIA-7A and the FERC-423 data bases were supplemented by the Bureau of Mines/EIA analytical file (maintained by EIA). This computer file provided additional data on in-seam coal qualities, which were used to represent the input characteristics to each of the preparation plants. The file contains several thousand analyses of in-place coal quality, correlated by coal seam and county within a given state; most of the analyses were performed in the 1940s and 1950s, but the file contains analyses dating from the turn of the century up to the present. In addition, bed/county coal quality figures from mines selling their product without any form of mechanical cleaning (obtained from EIA-7A Supplement) were added to the analytical file. Average bed/county Btu and sulfur estimates were then computed and used as input qualities to those preparation plants located in the same bed and county combination.

The data bases and systems described above were used to develop estimates of the extent to which SO₂ emissions are being reduced, at present, through physical coal cleaning. The second primary objective of this study was to determine the extent to which current SO₂ reduction can be improved through increased coal cleaning. In addition to the Bureau of Mines/EIA analytical file described above, washability data were used to meet this second objective. The primary source of these washability data was the U.S. Department of Energy (DOE), which has assembled a data base (available on computer tape from DOE's Pittsburgh Energy Technology Center) consisting of the results of washability tests performed on approximately 1,000 coal samples taken from major seams throughout the U.S. The DOE data base was supplemented with washability data obtained from a series of Reports of Investigation published by the U.S. Bureau of Mines from the late 1940s through the early 1970s. Data for approximately 100 coal samples, all taken from eastern seams, were obtained from the Bureau of Mines reports.

Data Problems

At the outset, it must be emphasized that serious problems existed with the data bases and systems described in the preceding section. Although these problems did not prove insurmountable, they undoubtedly had an adverse impact on the accuracy of the SO₂ reduction estimates. Essentially, there were two problems of major importance. First, none of the available data bases provides estimates of the sulfur content of the raw coal input to existing preparation plants. Second, there is a lack of washability data for much of the coal reserve base.

The EIA-7A (Supplement) data base, which contains the most comprehensive preparation plant data currently available, provides estimates of the sulfur content of the clean coal produced by existing plants, but without corresponding information on the sulfur content of the raw coal input to the plants it is obviously impossible to determine the amount of sulfur currently being removed through cleaning. Therefore, it was necessary to develop estimates of the quality of the raw input

to the plants. Briefly, the average raw sulfur content for *all of the coal* contained in each bed/county combination was used to approximate the sulfur content of the *raw input* to plants processing coal from the same bed/county combination.

The use of bed/county averages as approximations for the sulfur content of the raw coal input to preparation plants presents two main problems. First, the sulfur content of coal can vary significantly within the same bed/county combination; thus an average sulfur content for the entire bed/county combination is not necessarily representative of the sulfur content of the coal being mined in specific areas within the combination. Second, and more importantly, mine operators will tend to develop the lower-sulfur reserves contained in each bed/county combination before mining the higher-sulfur coal. Thus, the sulfur content of that portion of each bed/county's reserves that is currently being mined and cleaned will tend to be lower than the average sulfur content of all the coal contained in the bed/county combination. In other words, the use of bed/county averages as substitutes for the actual sulfur content of the raw coal input to preparation plants may well have biased the raw sulfur input estimates, and hence the current SO₂ reduction estimates, towards the high side.

The second major data problem -- the lack of washability data for much of the reserve base -- also reduced the accuracy of the potential SO₂ reduction estimates. As discussed in the preceding section, the potential reduction estimates were developed using washability data obtained from the Department of Energy and Bureau of Mines. These data were input into a coal cleaning model, which generated separate SO₂ reduction and cleaning cost estimates for each sample. The estimates developed for each sample were then assigned to that portion of the 1983 U.S. Demonstrated Reserve Base (DRB)² best represented by the sample. Specifically, the DRB was broken down into a large number of "blocks"; each reserve block was then assigned the SO₂ reduction and cost estimates corresponding to the washability sample most representative of the block.

When possible, assignments were made at the bed/county level; i.e., if washability data for x samples taken from a given bed, within a given county, were available, then the reserves contained in that bed/county combination were divided into x equal shares, and each share or block was assigned the SO₂ reduction and cost estimates corresponding to one of the x samples.

The problem was that for many bed/county combinations, x equalled zero; i.e., no washability data were available. It was therefore necessary to repeat the procedure outlined above at the county level for that portion of the DRB for which data were unavailable at the bed/county level. That is, the reserves contained in each bed/county combination for which x equalled zero were divided into y equal shares, where y equalled the number of reserves contained in the same county, *regardless of bed*. Again, each share or block was assigned the SO₂ reduction and cost estimates corresponding to one of the y samples. Even at the county level washability data were sometimes entirely lacking; thus it was necessary to repeat the reserve assignment procedure a third time, at the bed/region level, and finally a fourth time, at the regional level.* In short, the reserve assignment procedure involved the extension of washability test results from the samples

* Most of the regions defined for this study corresponded to states, but some regions (e.g., Eastern and Western Kentucky) consisted of portions of states.

upon which, the tests were performed to in-place reserves -- reserves that were often contained in beds and/or counties different from those from which the samples were taken. This no doubt reduced the accuracy of the potential SO₂ reduction estimates.

In Appendix B, an attempt is made to develop a quantitative assessment of the uncertainty introduced into the current and potential SO₂ reduction estimates as a result of the problems outlined above. Although this assessment is itself partly subjective and therefore uncertain, it should provide the reader with a rough feel for the accuracy of the SO₂ reduction estimates. Basically, the assessment indicates that the results of this study should be viewed as "ballpark" estimates of the amount of SO₂ that is currently being, and could potentially be, removed through physical coal cleaning. However, such rough estimates should suffice, and indeed prove useful, for a wide variety of analytical purposes. More to the point, rough estimates, such as those presented in this report and in other reports (see Chapter 3), will *have* to suffice unless and until an effort is made to obtain better, more complete data.

The data problems outlined above are not specific to this study; they appear in fact to be the fundamental problems hampering all efforts to assess the current and potential impact of coal cleaning on SO₂ emissions. As long as these problems continue to exist, rough estimates will be the best attainable. Therefore, if more precise SO₂ reduction estimates are needed, an effort to collect the required data will have to be initiated; this effort would require a considerable expenditure of time and resources. For example, in the case of the washability data, a substantial number of coal samples from throughout the country would have to be collected and then subjected to standardized washability tests. The number of required samples could be reduced to some extent by targeting those bed/county combinations containing particularly large quantities of reserves for which washability data are not now available, but even if this step were taken the number of required samples would still be substantial.

Although collecting data on the sulfur content of the raw coal input to existing plants would be considerably easier and less costly than obtaining washability data, a significant effort would be required to obtain these data as well. At a minimum, it would be necessary to conduct on-site visits to a sufficiently large sample of operating plants. SAIC made an unsuccessful attempt to obtain data on the sulfur content of the raw feed through a telephone survey of 109 plants, and is now convinced that the only way to obtain these data is by copying it from the laboratory reports available at the plant sites. In some cases it might even prove necessary to sample and analyze the raw feed, since many respondents to our telephone survey stated that they do not analyze the raw coal.

Given the magnitude of the effort that would be required to collect even raw sulfur content data, let alone washability data, the decision of whether or not to collect new data must be based on a balancing of the accuracy requirements for the SO₂ reduction estimates, versus the availability of the necessary financial resources.

Report Organization

The following chapters present the results of the overall analysis. Chapter 2 discusses coal preparation activities in each of the major coal producing regions and provides data on the amount of coal that is mechanically cleaned, as well as the breakdown by mining method,

cleaning level, and end-use market. Each mining region's distribution of steam coal to the major demand centers, including delivered quality and cleaning level, is also reviewed.

Chapter 3 presents information on current state-level SO₂ reduction levels. The first part of the chapter discusses in detail the method used to conduct the analysis of current SO₂ reduction; the second part contains state-by-state estimates of SO₂ reduction for all levels of preparation. Because the Environmental Protection Agency (EPA) has examined SO₂ reduction through coal cleaning in the past, Chapter 3 compares the results of previous studies with the current effort.

Chapter 4 presents the results of the analysis of potential SO₂ reduction from coal-cleaning. This analysis, conducted on a regional basis, estimates the SO₂ reduction potential from increasing both the amount of coal cleaned and the intensity of the cleaning activity. The chapter describes completely the methodological approach and the results of the analysis.

2. Regional Coal-Cleaning Analysis

Overview

Coal preparation removes impurities such as ash, sulfur, and moisture from "raw" or "run-of-mine" coal. Although different coals can vary widely in their purity, no coal is completely free of impurities. Most impurities enter the run-of-mine product in one of two ways. First, a portion of the impurities is present in the seam itself and is thus mined along with the coal. Second, mining itself adds impurities to the coal. As the seam is extracted, some of the rock adjacent to the seam is unavoidably removed along with the coal. In addition, small amounts of impurities can enter the coal as it is transported from the mine to the preparation plant and/or end-user due to exposure to precipitation.

Preparation removes a portion (but not all) of the impurities present in the seam itself and added during mining. The degree to which the impurity content of a coal can be reduced depends on the nature and characteristics of the raw coal and the intensity of the preparation process. Two preparation techniques can be defined: (1) crushing and screening and (2) mechanical cleaning. Crushing and screening is the simplest and cheapest, but the least effective, of the two techniques. Crushing and screening reduces oversized lumps and ensures that the size consistency of the coal particles meets the buyer's specifications; the technique can also be used to separate some of the larger lumps of rock that mix with the coal during mining. The process makes use of the fact that rock is harder to break than coal; thus, when raw coal is crushed to a point at which all of the coal particles can pass through the apertures of a given screen size, some of the rock particles will be retained on the screen surface.

Crushing and screening removes large chunks of rock adjacent to the seam, but it does not remove smaller rock particles or impurities present in the seam itself. For this, mechanical cleaning is necessary. The mechanical cleaning process incorporates crushing and screening as its first two steps, but also involves separation and dewatering. The specific gravity differences between coal particles and impurity particles make separation possible. For any given coal, the extent to which the impurities can be removed varies, depending on the design and operation of the plant. However, unlike crushing and screening, mechanical cleaning results in the loss of some coal along with the refuse. Because the amount of coal lost increases with the quantity of refuse material removed, the design and operation of mechanical cleaning plants (indeed, the decision as to whether mechanical cleaning is economically feasible) reflect trade-off considerations between coal quality and quantity.

Mechanical cleaning plants, unlike crushing and screening plants, can differ significantly in their complexity. Basically, as the required intensity of cleaning increases, the design of the plant becomes more complex. Because metallurgical coal typically must be subjected to intensive cleaning to meet the stringent quality requirements of metallurgical coal buyers, cleaning plants designed to produce a metallurgical-grade product tend to be highly complex. On the other hand, steam coal quality specifications tend to be less stringent and thus can be met with simpler plant designs. In many cases, crushing and screening plants provide adequate preparation for steam

coals, and in some cases a run-of-mine product can be used without preparation in power-plant boilers.

Typically, preparation plants are classified according to preparation level; throughout this report we have adopted this same classification scheme. The different preparation levels are defined as follows:

- Level 1 Preparation - crushing and screening only.
- Level 2 Preparation - A single cleaning circuit, designed to clean the coarse fraction of the raw input stream, is used. (The other size fractions may or may not be passed through the circuit.)
- Level 3 Preparation - Two separate cleaning circuits are used, one for coarse and one for mid-sized coal. (The fine-sized coal may or may not be passed through the mid-sized circuit.)
- Level 4 Preparation - Three (sometimes four) cleaning circuits are used, one for coarse, one for mid-sized, and one for fine coal.

Traditionally, ash reduction has been the primary objective of preparation. However, interest in the use of mechanical cleaning for sulfur removal has grown along with the concern for reducing SO₂ emissions from power plants. For the most part, mechanical cleaning can reduce only pyritic sulfur; organic sulfur is chemically bonded to the coal and thus cannot be removed through mechanical processes. Fortunately, pyritic sulfur typically constitutes the major portion of a coal's total sulfur content; from a technical standpoint, the overall potential for reducing sulfur through preparation is therefore quite high, even though, for some coal deposits with low inherent sulfur and/or small particle sizes, removal may prove troublesome. However, the key consideration is economic, not technical; any improvements in sulfur removal can be accomplished only at increased costs and/or coal losses.

Data limitations have hampered efforts to determine the economic potential for sulfur reduction through preparation, but the following chapters contain some order-of-magnitude estimates for current production from the major U.S. coal-producing districts.

Both the mining and preparation of a given production run of coal are typically handled by the same company. However, smaller mine operators, lacking the capital or the required production to support a separate plant, often sell their coal to larger mining companies that then feed the purchased coal, along with the coal produced by their own mines, into their preparation plants. Only a few companies specialize in coal preparation exclusive of mining.

In 1983, the last year for which data were available for this study, about 80 percent of total raw coal production underwent at least minimal preparation (crushing and screening). Over 50 percent of the total production was mechanically cleaned in over 400 plants scattered throughout the country. These 400 plants yielded about 70 percent of the raw coal input. Most of the mechanically cleaned coal (68 percent) was mined by underground methods; only 23 percent of surface-mined coal (versus 70 percent of underground-mined coal) was mechanically cleaned. There are two primary reasons for this difference. First, most U.S. metallurgical reserves are not amenable to surface mining. Because metallurgical coal invariably requires washing, while steam

coal often does not, the unequal distribution of metallurgical coal by mining method is in part responsible for the unequal distribution of mechanical cleaning by depth. Second, the rock particles adjacent to the seam that mix with the coal during surface mining tend to be larger, and therefore are more easily removed from the coal by crushing and screening alone, than is the case in underground mining, which often requires mechanical cleaning. The difference in the size of the rock particles depends on the method used to break the rock; in surface mining the rock is blasted, and in underground mining it is typically ripped from its place by mechanical means and in the process is crushed to a relatively fine size.

Coal Preparation Activities by Region

Coal preparation activities differ considerably by state and by coal-producing region. Differences in mining methods, geologic conditions, in-seam coal quality, and end-use markets all affect the type and degree of coal cleaning activities that take place. The following sections summarize the importance and degree of coal-cleaning for each of the major producing regions as shown in Figure 2.1. The data presented in this section come from the Form EIA-7A Supplement, a biennial survey form sent to all coal producers and processors whose annual production/output exceeds 90,700 metric tons (100,000 short tons) per year. Data collected by the Energy Information Administration (EIA) include total production; amount of total production mechanically cleaned, crushed and screened, or sold without preparation; end-use market for the coal; and mining method. While some problems exist with the nature of the survey frame, the information collected is fairly representative of overall coal preparation activities.

Central Appalachian Region

Central Appalachia, for the purposes of this study, is defined as the coal producing areas of eastern Kentucky, Tennessee, Virginia, and West Virginia. Coal preparation is quite important in this region. As shown in Table 2.1, of the 201 million metric tons (221.5 million short tons) of raw coal production coming from mines producing more than 90,700 metric tons (100,000 short tons) of coal per year, over 90 percent underwent at least some preparation. Of the raw coal prepared, 73 percent was mechanically cleaned, and 20 percent was crushed and screened. Remember, however, that these figures do not represent total production for the region; rather, they represent only the output of relatively large mines. The Form EIA-7A Supplement covers approximately 74 percent of Central Appalachia's total regional production. Based on experience, most coal from small mines in this region is not mechanically cleaned but, instead, is sold as a crushed and screened or run-of-mine product. Therefore, we believe that the total cleaning estimates for this region are to some degree inflated. For example, as Table 2.1 shows, we estimate that about 79 percent of the raw coal coming from West Virginia mines producing more than 90,700 (100,000) metric tons per year is mechanically cleaned. If we assume, based on our experience, that the production from small mines in West Virginia (in this case 21 million metric tons) is not mechanically cleaned, the percentage of raw coal that is washed drops from 79 percent of the output from relatively large mines to about 74 percent of the output from all mines located in the state.

West Virginia operators mechanically clean a larger percentage of their output than do operators in any of the region's other states, except Tennessee, a relatively minor coal-producing state. This

Figure 2.1. Major Coal-Producing Regions

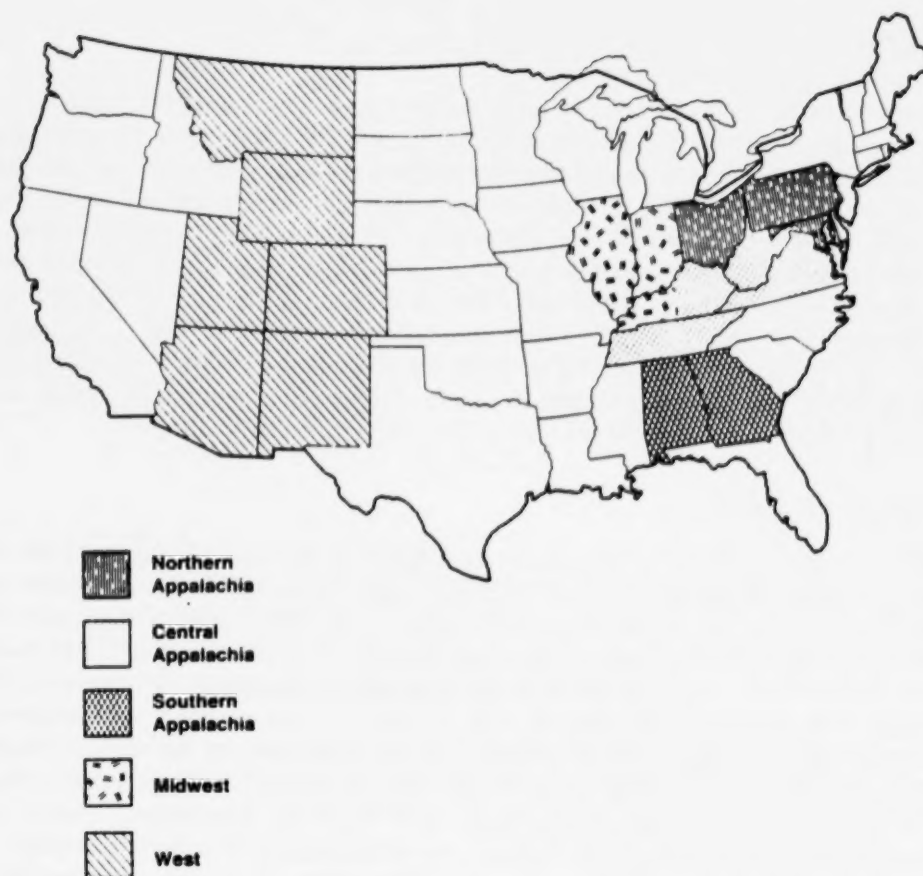


Table 2.1. Central Appalachian Coal Preparation (1983)

Area	Quantity of Coal Produced ^a	Quantity of Coal Mechanically Cleaned		Quantity of Coal Crushed & Screened		Quantity of Coal Not Prepared	
	(Million Raw Metric Tons)	Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total
E. Kentucky	50.7	29.1	57	13.6	27	8.0	16
Tennessee	4.2	3.4	80	0.8	20	0.0	0
Virginia	25.0	19.2	77	3.9	16	1.9	7
W. Virginia	121.0	96.1	79	22.5	19	2.4	2
<i>Total</i>	<i>200.9</i>	<i>147.8</i>	<i>74</i>	<i>40.8</i>	<i>20</i>	<i>12.2</i>	<i>6</i>

^aQuantity values represent production from mines producing more than 90,700 (100,000) metric tons of coal per year and reporting on Form ELA-7A Supplement.

signifies West Virginia's importance as a source of metallurgical coal for both foreign and domestic use. In all instances, coal sold as a coking product is mechanically cleaned. Although production of metallurgical coal has declined in recent years, evidence indicates that at least some of this output has made its way to the steam market.

The importance of preparation in Central Appalachia is manifested in the number of mechanical cleaning plants in operation there -- 158, more than half the U.S. total. The distribution of preparation plants by state is as follows:

Eastern Kentucky	40 plants
Tennessee	3 plants
Virginia	27 plants
West Virginia	88 plants
<i>Total</i>	<i>158 plants</i>

It is important to recognize that, although the region's plants (like all others in the nation) are almost always operated by mining companies, they are not necessarily tied to any specific mine. In fact, many of the plants in Central Appalachia serve a number of different mines -- a result of the structure of the Central Appalachian mining industry. Throughout this region, many of the mines are small, short-lived operations. Preparation plants, on the other hand, are built to remain operative for relatively long time periods (e.g., 30 years) and to take advantage of economies of scale that are more important in preparation than in Central Appalachian mining. A plant must process coal from a number of mines in order to maintain economies of scale. Plants may either be located at one of the operator's larger mines, or centrally located offsite. All plants are located near the mines they serve because one of the primary purposes of preparation is to reduce transportation costs by removing non-coal (ash) material from the run-of-mine product.

The available data for 1983, as presented in Table 2.1, show that mechanical cleaning reduced raw coal production from 200.9 million metric tons (221.5 million short tons) of output to 146.6 million metric tons (161.6 million short tons) of salable product. The clean-coal yield from the

Table 2.2. Method of Cleaning by Method of Mining^a

Producing Area	Underground			Surface		
	Percent Mech. ^b	Percent C&S ^c	Percent No Prep. ^d	Percent Mech.	Percent C&S	Percent No Prep.
E. Kentucky	77	13	10	19	55	26
Tennessee	84	16	0	N/A ^e	N/A	N/A
Virginia	76	16	8	30	38	32
W. Virginia	79	19	2	38	56	6
<i>Total</i>	<i>79</i>	<i>16</i>	<i>5</i>	<i>29</i>	<i>50</i>	<i>21</i>

^aPercentages based on run-of-mine output.

^bMech. = Mechanically cleaned.

^cC&S = Crushed and screened.

^dNo-Prep. = No preparation.

^eN/A = Data not available.

region's mechanical cleaning plants was approximately 64 percent. The clean-coal yields of individual states within this region were as follows: eastern Kentucky, 62 percent; Tennessee, 57 percent; Virginia, 59 percent; and West Virginia, 65 percent.

As is the case for the nation as a whole, the use of mechanical cleaning in Central Appalachia is highly correlated with mining methods. Table 2.2 provides a breakdown of cleaning activities on run-of-mine output by mining method for each of the region's producing areas. For the region as a whole, over 96 percent of the more than 100 million metric tons (110 million short tons) of raw coal output from underground mines was at least crushed and screened before being sold. However, a full 21 percent of surface production (7.6 million metric tons (8.4 million short tons)) was sold without any form of preparation, and another 50 percent (18 million metric tons (19.8 million short tons)) was crushed and screened only. Virtually all of the "no-preparation" coal was sold to electric utilities.

Like all other coal-producing regions, Central Appalachia sold most of its resource to the electric utility industry. North and South Carolina, Florida, Georgia, Michigan, and Wisconsin generated most of the demand for this coal. These states lie within the East North Central and South Atlantic census regions. The principal coal supplied by Central Appalachian producers to these supply regions was a high-quality bituminous product, averaging over 6,720 kcal/kg (12,000 Btu/lb), 1.0 percent sulfur, and 10 percent ash. To meet these quality specifications, a majority of the coal sold on this market was mechanically cleaned. For coal sold to the utility market in 1983, Table 2.3 lists the percentage of run-of-mine output that was mechanically cleaned, crushed and screened, or sold without preparation in each of Central Appalachian supply areas.

Comparing this table with Table 2.1 shows that, in all cases, the percentage of steam coal that was mechanically cleaned was significantly less than the overall splits computed for total production. One reason for this occurrence is that Central Appalachia is a major producer of metallurgical coal, which is almost always mechanically cleaned. Also, the utility market is cost sensitive; therefore, producers will clean their coal only if quality specifications so dictate.

Table 2.3. Cleaning Distribution for Coal Sold to Electric Utilities^a

Supply Area	Percent Mechanical	Percent Crushed & Screened	Percent No Preparation
E. Kentucky	40	38	22
Tennessee	69	31	--
Virginia	62	25	13
W. Virginia	69	29	2

^aPercentages based on run-of-mine output.

Southern Appalachian Region

Southern Appalachia, as defined here, includes the bituminous coal and lignite-bearing areas of Alabama and Georgia. Because Alabama is the only major producing state in the region, it is the only Southern Appalachian state for which data are available. Over the years, Alabama has undergone a considerable transformation with respect to coal preparation. In 1978, Alabama mines produced approximately 23.6 million metric tons (26 million short tons) of raw coal, of which 54 percent was mechanically cleaned, 12 percent was crushed and screened, and 34 percent was sold without any form of preparation. Changes in market conditions since then have significantly altered this cleaning distribution. In 1983, coal production in Alabama stood at about 26.3 million raw metric tons (29 million raw short tons). Since 1978, mechanical cleaning has risen from 54 percent to 79 percent of total production, and the amount of coal sold without any preparation has decreased from 34 percent to less than 5 percent of the state's output.

Raw coal inputs to preparation plants were approximately 20.8 million metric tons (23 million short tons), which translated into 13.6 million metric tons (15 million short tons) of salable product, a yield of 65 percent. The state contains about 30 operating plants, with jigs, magnetite, and froth flotation as the primary methods of preparation.

In terms of production by mining method, surface and underground operations yield approximately equal tonnages. All underground production is mechanically cleaned, compared with 38 percent (4.9 million metric tons (5.4 million short tons)) of the surface-mined coal. About 50 percent (6.6 million metric tons (7.5 million short tons)) of the surface production is crushed and screened, with the remaining 12 percent (1.5 million metric tons (1.7 million short tons)) sold without any preparation.

Of the salable coal product coming out of Alabama, 60 percent (15.8 million metric tons (17.4 million short tons)) was sold to the domestic electric utility industry. The principal buyers of Alabama coal were utilities in the states of Alabama, Mississippi, and Tennessee. Nearly 70 percent (11 million metric tons (12.1 million short tons)) of the coal sold to these utilities was mechanically cleaned, 24 percent (3.8 metric tons (4.2 million short tons)) was sold crushed and screened, and the remaining 6 percent (1 million metric tons (1.1 million short tons)) was sold directly as mined. Most of the mechanically cleaned coal was sold to utilities within Alabama. Most coal sold to utilities in Mississippi and Tennessee was crushed and screened; some was sold

directly as mined. Mining method appears to be the principal factor behind differences in the degree of preparation among coal shipments to each of these states. Over 60 percent of all steam coal burned in Alabama comes from underground mines located within the state. All Alabama coal sold to Mississippi and Tennessee utilities is shipped exclusively by contract and comes from relatively small surface mines that mechanically clean their coal only if required to meet contract specifications. About 12 percent of Alabama coal was sold within the state via the spot market.

Northern Appalachian Region

For the purposes of this discussion, Northern Appalachia consists of Pennsylvania, Ohio, and Maryland. Like data for all other regions, the cleaning figures presented in this discussion are based on data from mines producing more than 90,700 million metric tons (100,000 short tons) per year. Mines in this tonnage class account for over 84 percent of this region's total output. The cleaning estimates should therefore be representative of the region as a whole.

The percentage of raw coal that is prepared (mechanically cleaned or crushed and screened) is slightly lower in Northern Appalachia than in Southern Appalachia (see Table 2.4). Of the total 1983 raw coal production of 103 million metric tons (114 million short tons), 92 percent (versus 94 percent for Central Appalachia) was prepared. Of the quantity that received some form of cleaning, 22 percent was crushed and screened and 70 percent was mechanically cleaned. Northern Appalachia's coal undergoes less mechanical cleaning than Central Appalachia's; in Central Appalachia, about 74 percent of the total raw coal production was mechanically cleaned. Of particular interest here is Ohio, which mechanically cleaned 82 percent of its raw production. This is a dramatic change from 1978 (the last year before 1983 for which figures are available), when only 47 percent of the coal was prepared in this manner. This increase in mechanical cleaning reflects the changes that have occurred in the marketplace over the past several years.

In 1983, over 85 mechanical cleaning plants were in operation in Northern Appalachia -- about 20 percent of the U.S. total. Pennsylvania, by far the largest coal-producing state in the region

Table 2.4. Northern Appalachian Coal Preparation (1983)

Area	Quantity of Coal Produced ^a (Million Raw Metric Tons)	Quantity of Coal Mechanically Cleaned		Quantity of Coal Crushed & Screened		Quantity of Coal Not Prepared	
		Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total
Maryland	5.39	3.12	58	1.42	26	0.84	16
Ohio	33.39	27.35	82	4.68	14	1.37	4
Pennsylvania	64.35	41.70	65	16.16	25	6.49	10
<i>Total</i>	<i>103.13</i>	<i>72.17</i>	<i>70</i>	<i>22.27</i>	<i>22</i>	<i>8.70</i>	<i>8</i>

^aQuantity values represent production from mines producing more than 90,700 (100,000) metric tons of coal per year and reporting on Form EIA-7A Supplement.

and the only state with any appreciable reserves of metallurgical coal, contains most of these plants.

Most cleaning plants in this region are tied primarily, or exclusively, to a single mine -- a departure from the pattern that prevails in Central and Southern Appalachia. The principal reason for this difference is that the mines in Northern Appalachia (particularly underground mines) tend to be larger and longer lived than those in Central or Southern Appalachia. Based on EIA-7A data, only 28 percent of the active mines in Central Appalachia produce more than 90,700 metric tons (100,000 short tons) per year. This compares with over 40 percent of the mines operating in Northern Appalachia.

Preparation reduced Northern Appalachia's total 1983 raw production from mines in the 90,700 million metric tons (100,000 metric tons) and greater classification from 103 million metric tons (114 million short tons) of output to 82.9 million metric tons (91.4 million short tons) of salable product, a material loss of about 20 percent. The yields from mechanical cleaning are 76 percent, 70 percent, and 71 percent for Maryland, Ohio, and Pennsylvania, respectively. These yields considerably exceed those associated with the mining areas of Central Appalachia. The difference in yields for the two regions partly reflects the fact that Northern Appalachia coal seams tend to be thicker (an average of 1.63 meters (5.35 feet) meters for Northern Appalachia versus an average of 1.37 meters (4.49 feet) for Central Appalachia, based on 1983 EIA-7A data), thus reducing the amount of dilution material added to the coal during the mining process. Also, much of the coal cleaning in Central Appalachia is for metallurgical purposes, and thus entails a generally more intensive process than the preparation of steam coal.

Mining method again plays an important role in determining the amount of preparation the coal receives before sale to the end-user. For Pennsylvania and Ohio, the dominant mining states in the region, the breakdown of cleaning by mining method for coal sold to the various end-use markets is as follows:

- Pennsylvania
 - 66 percent of underground production is mechanically cleaned
 - 41 percent of surface production is mechanically cleaned
- Ohio
 - 90 percent of underground production is mechanically cleaned
 - 65 percent of surface production is mechanically cleaned

These figures show that more underground production than surface production is cleaned. However, there appears to be no difference in the way the coal from each mining method is cleaned. In both states, and for both mining methods, the dominant method of cleaning is the use of jigs, followed by magnetite and concentrating tables. Froth flotation and sand were also significant cleaning methods for Pennsylvania underground coal.

The low quality of Ohio's in-place reserves forces that state's producers to mechanically clean more of their output than do Pennsylvania producers; this explains the percentage differences between the two states. Reserves in Ohio are typically a high-sulfur, medium-Btu, high-ash

product. In today's highly competitive, quality-conscious market, producers in Ohio must upgrade their product to compete even within their traditional market areas. As for the distribution of production by end-use category, the domestic utility industry purchases approximately 75 percent of Northern Appalachia's total salable product. This output is sent primarily to the Middle Atlantic states of Pennsylvania, New York, and New Jersey, as well as to Ohio, Maryland, Delaware, and Michigan in the East North Central and South Atlantic census regions.

Pennsylvania coal sold in Pennsylvania comes primarily from underground mines (61 percent in 1983). This coal has average quality characteristics of 6,832 kcal/kg (12,200 Btu/lb), 1.8 percent sulfur, and 15 percent ash. Approximately 70 percent of the coal is mechanically cleaned; most of the remainder is crushed and screened before shipment to the end-user. The second largest buyer of Pennsylvania steam coal is New York. The vast majority of coal purchases by utilities in New York comes from surface mines (94 percent in 1983), and while the quality characteristics are similar to those of coal purchased by Pennsylvania utilities, less than 40 percent of the coal shipped to New York is mechanically cleaned. Delaware utilities purchase over 1 million tons of Pennsylvania surface-mined coal per year. The coal purchased is a high quality bituminous product with quality characteristics of over 7,056 kcal/kg (12,600 Btu/lb), less than 1.5 percent sulfur, and about 11 percent ash. Over 50 percent of this coal is mechanically cleaned.

Most of Ohio's steam coal is sold within the state. As mentioned previously, because of the relatively poor quality of in-place reserves, a large majority of the steam coal production must be mechanically cleaned before marketing. The average delivered quality of Ohio coal sold to Ohio utilities is 6,496 kcal/kg (11,600 Btu/lb), 3.3 percent sulfur, and 10 percent ash. In Pennsylvania, the Btu content is higher (6,832 kcal/kg), but so are the sulfur and ash content: 3.8 percent and 11.6 percent, respectively. Ohio coal sold to utilities in Michigan comes exclusively from underground mines and is all mechanically cleaned before shipment; delivered quality averages 6,272 kcal/kg (11,200 Btu/lb), 2.4 percent sulfur, and 11 percent ash. As the numbers indicate, even with mechanical cleaning, Ohio coal delivered to Michigan is not of high quality. Because a third of Ohio's preparation plants are single-circuit operations, it appears that more intensive cleaning could improve quality substantially. This area will be explored in greater detail later in this report.

Midwestern Region

The Midwestern producing region is made up of the coal-producing areas of Illinois, Indiana, and western Kentucky. Of producers in the regions discussed so far, Midwestern producers prepare the highest percentage of their overall raw coal output. Table 2.5 provides a breakdown of coal cleaning activities for each of the producing areas in this region. Of the 133 million metric tons (147 million short tons) of raw coal production coming from mines producing more than 90,700 million metric tons (100,000 million short tons) per year, 95 percent was either mechanically cleaned or crushed and screened. Because mines in this size class produce about 98 percent of the region's total output, the cleaning figures presented are representative of current activities.

A great deal of this region's coal is mechanically cleaned. Illinois producers wash about 93 percent of their total raw coal output. Even in Indiana, where almost all of the production comes from surface mining operations, over 70 percent of total output is washed. In Illinois and western

Table 2.5. Midwestern Coal Preparation (1983)

Area	Quantity of Coal Produced ^a	Quantity of Coal Mechanically Cleaned		Quantity of Coal Crushed & Screened		Quantity of Coal Not Prepared	
	(Million Raw Metric Tons)	Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total	Million Raw Metric Tons	% of Total
Illinois	63.0	58.9	93	3.5	6	0.6	1
Indiana	33.7	26.2	78	5.8	17	1.7	5
W. Kentucky	36.5	26.0	72	6.6	18	3.8	10
<i>Total</i>	<i>133.2</i>	<i>111.1</i>	<i>83</i>	<i>15.9</i>	<i>12</i>	<i>6.1</i>	<i>5</i>

^aQuantity values represent production from mines producing more than 90,700 (100,000) metric tons of coal per year and reporting on Form EIA-7A Supplement.

Kentucky, where production is evenly split between surface and underground mines, mining method has less bearing on cleaning level than in the other producing regions.

As a result of preparation, the 133 million metric tons (147 million short tons) of raw production was reduced to 104 million metric tons (115 million short tons) of salable product. This represents a material drop of about 22 percent. The overall mechanical cleaning yield for the region was 74 percent, significantly higher than yields for the coal-producing areas of Appalachia (64 percent, 65 percent, and 70 percent for Central, Southern, and Northern Appalachia, respectively). This difference can be attributed to the fact that very little metallurgical coal is mined and prepared in the Midwest. Yield figures for Midwestern preparation plants therefore do not reflect the cleaning losses associated with the intense preparation of this product type. As is the case with most steam coal cleaning plants, the principal method of preparation in this region is the use of jigs. In fact, all Indiana coal is prepared by this method. Magnetite plants in Illinois and western Kentucky account for about 19 percent of total cleaning activities, or approximately 11.8 million metric tons (13 million short tons) of salable coal. All the magnetite plants in this region are three-circuit (i.e., level 4) operations, indicating fairly intense preparation. Of the 11.8 million metric tons (13 million short tons) prepared in this manner, 8.2 million metric tons (9 million short tons) came from underground mines, mostly in western Kentucky.

As indicated earlier, most of this region's product is sold to electric utilities as steam coal. In Illinois, 86 percent of the total salable output was sent to the utility market. In Indiana, this figure is again 86 percent of salable output, and in western Kentucky, 92 percent of production went to electric utilities. Of this production, 91 percent, 72 percent, and 65 percent was mechanically cleaned in Illinois, Indiana, and western Kentucky, respectively. These percentages provide insight into differences between in-place reserves and mining methods. Of the states within this region, Illinois has the lowest quality reserves, followed by Indiana and western Kentucky. This correlates with the preparation percentages shown above. In terms of mining method differences, almost all production from underground mines in Illinois comes from continuous or long-wall mining operations, which yield a finely crushed product that is usually diluted by material from the roof and floor. The combination of relatively low in-seam quality and added dilution from mining dictates high degree of mechanical cleaning.

On the other hand, a significant portion of the production from underground mines in western Kentucky comes from conventional mining, in which the coal is broken by explosives rather than ripped from the face. Relatively large chunks result, from which crushing and screening can remove a good percentage of the foreign material. The higher the quality of in-place reserves, and the less they have been diluted in the mining process, the greater the effectiveness of crushing and screening.

Because of the generally low quality of the coal produced in this region, little is shipped outside the immediate area. Coal produced in Illinois is burned primarily by power plants located in Illinois and Missouri. As indicated before, almost all of the coal is mechanically cleaned. The average quality of the cleaned coal burned in Illinois is 5,990 kcal/kg (10,700 Btu/lb), 3.0 percent sulfur, and 10 percent ash. In Missouri, the average coal qualities are slightly higher: 6,160 kcal/kg (11,000 Btu/lb), 2.4 percent sulfur, and 9.9 percent ash. All utility coal burned in Missouri is mechanically cleaned, while some of the coal burned in Illinois is simply crushed and screened or used without preparation, hence the difference in quality.

Most steam coal produced in Indiana is burned within the state. Although this coal receives less mechanical cleaning than production from Illinois, the overall quality of the delivered product is somewhat higher. The average quality characteristics of local coal burned by Indiana power plants are 6,104 kcal/kg (10,900 Btu/lb), 2.6 percent sulfur, and 10 percent ash. For the limited quantity of Indiana coal shipped outside the state, the same quality characteristics hold true.

Of the 27.2 million metric tons (30 million short tons) of steam coal produced in western Kentucky in 1983, about 10.9 million metric tons (12 million short tons) were burned by utilities within the state. While 65 percent of the overall steam coal produced in western Kentucky is mechanically cleaned, less than half the coal burned within the state is washed. The average quality of western Kentucky coal burned locally is 6,104 kcal/kg (10,900 Btu/lb), 3.6 percent sulfur, and 14 percent ash.

In contrast, Tennessee is the second largest user of steam coal produced in western Kentucky coal (7.3 million metric tons (8.0 million short tons) in 1983). Over 80 percent of the western Kentucky coal shipped to Tennessee was mechanically cleaned. This condition is reflected in the average quality of the delivered product: 6,608 kcal/kg (11,800 Btu/lb), 2.7 percent sulfur, and 8.6 percent ash. Similar patterns exist for the remaining tonnage -- when less than 50 percent of the coal shipped was mechanically cleaned, sulfur content was above 3 percent; when a majority of the coal was washed, sulfur in the delivered product was as low as 2.4 percent.

Western Region

Little can be said about coal preparation in the Western coal-producing districts. For the most part, coal produced in this region is a subbituminous product, none of which is mechanically cleaned. Bituminous coal, for use by electric utilities, is mined in Colorado, Utah, and, to a much lesser extent, New Mexico. Utility coal mined in these states is inherently low-Btu, low-sulfur, and low-ash, thereby not requiring extensive cleaning. Only 6 percent of the utility coal mined in Colorado in 1983 was mechanically cleaned. In Utah, the figure was about 13 percent of utility coal production, and in New Mexico, less than 1 percent of the steam coal was cleaned. However, while very little coal produced in this region is mechanically cleaned, over 80 percent of all production (both bituminous and sub bituminous) is crushed and screened.

Demand for Compliance Coal

As the demand for low-sulfur compliance coal grows, coal-cleaning becomes increasingly important. Therefore, we thought it valuable to examine current activities in the compliance coal market. Of specific interest is the low-sulfur coal demand from those states purchasing most, or all, of their coal from the Appalachian and Midwest producing regions. For the purposes of this discussion, compliance coal is defined as coal with 1.08×10^{-6} kg/kcal (0.6 lb/MMBtu) or less of sulfur.

Table 2.6 provides information on the fraction of total coal purchases that fall into the compliance coal category for the years 1980 through 1985. As expected, those states in or near the low-sulfur coal producing regions of the West use a lot of compliance coal, while the major coal-burning states in the East and Midwest depend less on this coal type because of, among other factors, price and availability. Of particular interest, however, are those states with reasonable access to both compliance and non-compliance coal. One would expect that market forces affecting demand by coal type would be evident among this group of "swing states." Referring to Table 2.6, little change has occurred in the overall demand for compliance coal for the years 1980 through 1985. While individual states show some fluctuation, the basic trend has remained relatively flat. Table 2.7 examines these swing states, showing the changes that have occurred in compliance coal demand since 1972.

The states listed in Table 2.7 represent a group of coal buyers that have shifted a significant amount of their coal demand from traditional supply sources in the East and Midwest to the low-sulfur coal producing areas of the West. Some of the shift can be attributed solely to cost competition among the producing regions. Thick seam coal deposits found close to the surface, coupled with the economies of scale associated with the large scale mining operations that dominate the West, make production from this region relatively inexpensive. Compliance with air quality standards, however, plays an equally important role in determining demand for low sulfur coal. As concerns over air quality grew during the 1970s, so did the penetration of Western compliance coal into these swing states. These concerns reduced the importance of the basic delivered price per ton as utilities began thinking in terms of system-wide costs of compliance.

Some of this can be seen by examining current Federal Energy Regulatory Commission (FERC) data on delivered coal prices. In 1985, compliance coal from Wyoming delivered to utilities in Illinois had an average price in excess of \$63 per metric ton (\$57 per short ton). This compares with \$39 per metric ton (\$35 per short ton) for 2.0 percent-sulfur coal mined in Illinois. Compliance coal shipped to Mississippi from Utah and Colorado had a delivered price of over \$75 per metric tons (\$70 per short ton), compared with \$50 per metric ton (\$45 per short ton) for 1.5 percent sulfur Alabama coal. Very low-sulfur coal being burned outside of the major producing areas of the West carries a premium price that, at least at present, utilities appear willing to pay. Table 2.8 compares compliance and non-compliance delivered prices for most states that burn both coal types. The prices presented in this table are for coal purchased under long-term contract.

Of the states listed in Table 2.8, only in Iowa is compliance coal priced less than higher-sulfur coal types. The exact reason for the phenomenon is uncertain; however, it may arise in part from the financial ties between Iowa utilities and mining operations in Campbell County, Wyoming.

Table 2.6. Compliance Coal as a Percentage of Total Coal Purchases (1980-1985)

State	1980	1981	1982	1983	1984	1985
Massachusetts	0.00	0.40	1.00	6.74	3.26	2.78
New Jersey	8.66	6.29	10.46	11.77	10.94	16.93
New York	1.29	0.00	0.39	0.00	0.26	0.84
Pennsylvania	0.63	0.84	0.57	0.74	1.34	0.67
Illinois	32.97	38.71	27.98	22.72	26.71	33.21
Indiana	10.15	12.64	14.43	11.27	13.56	19.03
Michigan	34.95	37.48	34.71	38.81	40.50	49.55
Ohio	11.90	10.58	10.32	9.55	8.55	8.45
Wisconsin	24.87	34.80	32.13	34.85	36.96	48.10
Iowa	65.27	69.18	71.58	71.97	74.11	70.83
Kansas	76.60	76.85	74.28	80.71	81.14	80.00
Missouri	17.60	20.16	14.14	12.57	14.77	13.83
Louisiana	87.48	85.66	92.03	99.99	97.08	95.33
Texas	41.38	43.58	43.97	43.38	44.52	48.29
Alabama	14.62	14.90	23.38	21.26	18.49	15.78
Kentucky	13.91	19.06	17.95	17.10	12.22	8.29
Mississippi	30.91	45.13	42.31	43.40	39.34	39.20
Tennessee	1.67	0.09	1.00	1.08	0.78	0.88
Florida	10.27	8.45	19.36	24.87	24.20	29.37
Georgia	4.98	4.24	8.43	8.81	11.08	11.22
N. Carolina	12.42	16.58	17.49	20.26	19.91	19.11
S. Carolina	1.37	0.42	1.08	0.27	0.10	0.29
Virginia	26.78	18.78	23.33	31.79	29.27	35.30
W. Virginia	16.95	18.22	18.96	16.81	19.46	21.82
Arizona	99.34	99.33	97.46	94.54	94.03	97.23
Colorado	96.50	98.99	99.06	99.56	99.99	99.76
Utah	97.13	96.58	95.68	99.99	91.80	96.83
Wyoming	58.19	57.87	58.10	63.22	56.97	58.76

In addition to demand and contract pricing changes in the compliance coal market, changes have also taken place in the spot market. For the past several years, the trend by electric utilities has been away from long-term contracts. The stable world-wide energy situation and persistent overcapacity in the coal industry has created a buyer's market. Overall, the use of spot market purchases and short- and mid-term contracts is on the increase. The long-term contracts being written appear to have liberal renegotiation provisions/escape clauses, giving utilities great flexibility in the development of this overall fuel procurement strategy.

In the past, long-term supply contracts were viewed as necessary for price control. Throughout the 1970s, spot market prices were consistently higher than the contract price for similar grades of coal. Starting around 1980, the situation reversed and spot market prices fell sharply.

Table 2.7. Compliance Coal as a Percentage of Total Statewide Coal Demand (1972-1985)

State	1972	1978	1985
Indiana	3.10	10.84	19.03
Illinois	7.96	27.42	33.21
Michigan	3.83	20.01	49.55
Wisconsin	1.91	14.36	48.10
Mississippi	0.00	15.46	39.20
Kansas	0.00	51.66	80.00
Iowa	0.00	37.46	70.83
Missouri	2.10	3.84	13.83

Table 2.8. 1985 Compliance Coal and Non-Compliance Coal Price Comparison (\$/Metric Ton)

State	Compliance Coal	Non-Compliance Coal
Massachusetts	67.34	62.84
Illinois	62.19	42.20
Indiana	64.99	34.35
Michigan	49.09	43.73
Ohio	54.90	46.80
Wisconsin	46.07	39.29
Iowa	27.22	40.84
Kansas	27.73	26.21
Alabama	71.69	51.43
Mississippi	81.07	57.35
Kentucky	62.39	34.37
Florida	68.29	57.95
Georgia	79.49	48.12
N. Carolina	55.16	53.96
Tennessee	48.40	44.78

Table 2.9 provides data on 1985 spot market prices for both compliance and non-compliance coal purchased by electric utilities. Comparing the information in Tables 2.8 and 2.9, it is evident that spot market prices remain depressed relative to contract coal prices. This situation may eventually affect coal preparation because producers are less likely to develop reserves that require mechanical cleaning if the product must compete on the spot market.

Table 2.9. 1985 Spot Market Price Comparison (\$/Metric Ton)

State	Compliance Coal	Non-Compliance Coal
Massachusetts	59.00	62.86
Illinois	55.78	31.66
Indiana	57.43	33.01
Michigan	48.95	46.24
Ohio	42.21	35.38
Wisconsin	30.78	29.78
Iowaa	N/A	N/A
Kansasa	N/A	N/A
Alabama	39.00	37.84
Mississippi	--	47.97
Kentucky	36.03	33.01
Florida	53.21	47.02
Georgia	53.48	48.15
N. Carolina	44.09	43.05
Tennessee	38.48	35.64

^aSeparate prices for compliance and non-compliance spot market coal are not available.

3. Current SO₂ Reduction

Methodology

The methodology for determining current SO₂ reduction levels was structured to take maximum advantage of the new 1983 EIA-7A Supplement data. These data, in addition to providing mine and preparation plant-level information on the quantity of coal mechanically cleaned, crushed and screened, and not prepared, also provide "as-shipped" coal quality data for all mines and preparation plants producing over 90,718 metric tons (100,000 short tons) per year. The as-shipped quality of mechanically cleaned coal can be assumed to represent the output quality of the preparation plant. Thus, the EIA-7A Supplement data provide clean coal sulfur content data for all plants producing over 90,718 metric tons (100,000 short tons) annually.

Unfortunately, the EIA-7A data base does not provide information on the sulfur content of the raw coal input to preparation plants. Thus, in order to estimate the amount of sulfur removed through preparation, it was necessary to estimate the average sulfur content of the raw coal input to each preparation plant covered in the EIA-7A data base. Making these raw sulfur estimates proved to be the most involved and time-consuming part of this task.

As a first step in the estimation of raw sulfur inputs, the average raw sulfur content was estimated for all bed/county combinations for which data were available. Two data sources were used to develop these bed/county averages: the EIA/U.S. Bureau of Mines (USBM) analytical file, and the 1983 EIA-7A Supplement data. The USBM analytical file contains the results of lab analyses of samples taken from coal shipped to government facilities as well as the results of core drillings and face and channel samples. Most of these samples were taken during the 1940s and 1950s, but the file includes samples from the early part of the century up through the 1970s. The bed and county of origin are identified for each sample, and a distinction is made between raw and clean coal samples. At least one raw coal sample covers each of 1688 bed/county combinations.

The coal quality information in the 1983 EIA-7A data base was used to supplement the USBM/EIA data. Although the sulfur content data in this data base are reported on an as-shipped (dry) basis, the as-shipped sulfur contents should equal the raw coal sulfur contents for those mines that do not mechanically clean any coal. Thus, we identified those mines that, in 1983, did not wash any of their product; and we used the average sulfur contents reported by these mines as measurements of the raw quality of the bed/county combinations in which they were operating. Mines that derived less than 90 percent of total production from one bed were excluded from consideration, because in these cases, the reported sulfur content represented the quality of the coal mixture and not of the individual beds. (The cutoff was 90 percent rather than 100 percent, because slight dilution of the primary coal is tolerable, having little effect on the average sulfur content.) At least one usable EIA-7A raw sulfur measurement covered each of 188 bed/county combinations; many of these combinations were, of course, also covered by the USBM/EIA analytical file data. Merging the raw sulfur measurements from the EIA-7A data base and the USBM/EIA analytical file, and averaging the measurements by bed/county combination, yielded a file containing estimates of the raw sulfur content of over 1600 bed/county combinations.

The reader may wonder why arithmetic averages were used in developing the bed/county raw sulfur estimates rather than averages weighted by the quantities of coal shipped or produced to which the sulfur measurements correspond. This approach was taken because, typically, the quantity of coal shipped or produced is very small relative to the total quantity of reserves constituting a bed/county combination. Thus, the raw sulfur measurements from the USBM/EIA analytical file and EIA-7A data base are best regarded as point measurements; that is, as measurements corresponding to geographic points within a given county. Ideally, the spatial distribution of these points would be used to define the "area of influence" of each point and, then, the sulfur measurements would be weighted by the areas of influence. However, determining the area of influence of each individual sulfur measurement would be an enormous undertaking, far surpassing the scope of this project. By using the arithmetic average of the sulfur measurements falling in each bed/county combination as an estimate of the combination's raw sulfur content, we are implicitly assuming that the areas of influence corresponding to the measurements are equivalent.

To use our bed/county raw sulfur content estimates, we had to be able to trace the raw coal input to the preparation plants included in the EIA-7A data base back to the originating beds and counties. The EIA-7A Supplement form requires respondents to report the name and location of the preparation plant(s) that processed their coal; in addition, the EIA-7A form completed by all mines producing over 9,070 metric tons (10,000 short tons) per year, requires respondents to report their county location and to provide a percentage breakdown of their production by seam. All of this information is entered into the computerized EIA-7A data base except for the preparation plant names and locations; thus, to trace the plant input stream back to the source mines, it was necessary to review the EIA-7A forms manually. The result of this review was a list that matched mine identification (ID) numbers (taken from the forms) with plant names and locations. To use this information, the plant names had to be converted to EIA-7A ID numbers.

In many cases, plant names but no company names were found or a company name but no plant name was given, complicating the matching process. However, using the Automated EIA Respondent Reporting System (AERRS) file of company and mine/plant names, addresses, and IDs, along with the 1982 and 1985 Keystone Coal Industry Manuals,³ most of the required matches/conversions were made. Once the matching was completed, the mine ID-plant ID match file was entered into the computer and used to identify the mines served by each plant.

It should be noted that because the EIA-7A Supplement form is completed only by mines that produced over 90,700 metric tons (100,000 short tons) during the year, our mine ID-plant ID match file excludes the smaller mines served by plants that process coal from both mines producing less than 90,700 metric tons (100,000 short tons) per year and those producing more than 90,700 metric tons (100,000 short tons) per year.

The significance of this problem varies from state to state, depending on the percentage of each state's total tonnage produced by small mines. As Table 3.1 shows, small mine production is typically relatively low compared to the total production for all mines; therefore the problem should, in general, be relatively insignificant. However, in some states, particularly in central Appalachia, small mines produce a significant portion of the total production. (For central Appalachia as a whole, 26 percent of the total regional production came from mines that produced less than 90,700 metric tons (100,000 short tons) in 1983.) In these states, the exclusion of small mines from the mine ID-plant ID match file undoubtedly caused inaccuracies in our

Table 3.1. 1983 Production for Small Mines

State/ Region	Total 1983 Production ^a (Thousand Metric Tons)	
	Mines Producing Less Than 40,700 Metric Tons in 1983 ^b	All Mines ^b
Alabama	1,966	21,432
Colorado	511	15,163
Eastern Kentucky	25,979	84,549
Illinois	258	51,569
Indiana	1,388	28,838
Iowa	172	334
Missouri	439	4,513
New Mexico	34	18,519
Ohio	4,621	30,465
Pennsylvania	9,664	59,067
Tennessee	2,991	5,957
Utah	423	10,665
Virginia	13,870	31,313
West Virginia	16,085	103,681
Western Kentucky	1,690	41,362

^aIncludes both cleaned and raw production.

^bExcludes mines that produced less than 9,070 metric tons in 1983.

effort to trace the raw coal plant input streams back to the mine level. However, it is believed that a smaller percentage of the coal produced by small mines is cleaned than is the case for larger mines. Thus, the inaccuracies resulting from the exclusion of small mines should not be great.

In addition to determining the source mines for the coal input to the plants, we also had to determine the quantity of coal contributed by each mine to the plant input streams. All mines producing over 90,700 metric tons (100,000 short tons) per year are required to report the quantity of their product that was mechanically cleaned (on both a raw and clean ton basis), crushed and screened only, and shipped without preparation. Likewise, preparation plants are required to subdivide the total quantity of coal that they shipped during the year into the quantity that was mechanically cleaned, crushed and screened only, and shipped without preparation. Using these data, the following procedure was employed to estimate the quantity of coal received by each plant from each source mine:

- If a given plant reported that all of the tonnage it shipped was mechanically cleaned, then the quantity of coal shipped to the plant by each mine served by the plant was set equal to the quantity of raw coal that each mine reported as having been mechanically cleaned.
- If a given plant reported that some of the coal it shipped was crushed and screened only, and/or shipped without preparation, it was assumed that the as-shipped sulfur content reported by the plant represented an average of the sulfur contents of the coal that was mechanically cleaned, the coal that was merely crushed and screened, and the coal that was shipped without preparation. Thus, to ensure that our estimate of the raw sulfur input to the

plant corresponded to the same material as the reported as-shipped sulfur content, the quantity of coal shipped to the plant by each mine was set equal to the sum of the quantity of coal reported by the mine as having been mechanically cleaned (on a raw tonnage basis), the quantity reported as crushed and screened, and/or the quantity reported as shipped without preparation.

The quantity of coal shipped by each mine to the plant serving the mine was subdivided into bed/county quantities using the breakdown of the mine's total production by bed that is included in the EIA-7A data base, along with the county location of the mine. Then, by combining these bed/county quantities with the bed/county raw sulfur estimates previously developed, a weighted average raw sulfur content for the input stream to each plant was calculated. When this calculation had been made, the quantity of sulfur removed from the coal by each preparation plant could be determined as follows:

$$(R + CS + NP) S_R - (C + CS + NP) S_c = S_p \quad (1)$$

where

S_p	=	quantity of sulfur (in short tons) removed by the plant.
S_R	=	quantity of sulfur in the raw coal input to the plant (as a fraction of the total quantity of raw coal), estimated using the procedure described in the preceding pages.
S_c	=	quantity of sulfur in the coal shipped by the plant (as a fraction of the total quantity of coal shipped), taken from the plant data contained in the EIA-7A data base.
R	=	quantity of raw coal (in tons) mechanically cleaned by the plant.
C	=	quantity of clean coal (in tons) produced by the plant.
NP	=	quantity of coal (in tons) loaded for shipment without processing by the plant.
CS	=	quantity of coal (in tons) crushed and screened (but not cleaned) by the plant.

It should be clear, from the preceding procedural description, that it was not possible to calculate a value for S_p for every preparation plant included in the EIA-7A data base. For example, if a mine indicated that it shipped its coal to more than one plant, there was no way to determine what percentage of the total quantity of coal it shipped to each plant; thus, it was necessary to exclude from consideration all plants that received coal from mines shipping to more than one plant. Likewise, plants whose names could not be matched to EIA-7A ID numbers were excluded from consideration along with plants not co-located with mines and not reported as having received coal from any mines. Plants not co-located with a mine were always assumed to have cleaned the prepared coal shipped by the co-located mine, unless that mine reported that it shipped its coal to a plant or plants other than the onsite plant. These plants were also excluded from consideration. Finally, we excluded a plant whenever we estimated that we could not account for 10 percent or more of the coal shipped to it for any of the following reasons:

- A mine or mines that reported having shipped coal to the plant during the year (i.e., that reported the plant name and location on its EIA-7A Supplement form) reported zero tonnage as the quantity of its product cleaned during the year (unless the plant reported that it shipped some coal without preparation).
- The EIA-7A data base did not provide a breakdown of the total production of a mine or mines served by the plant by bed.
- The plant received coal from a bed/county combination for which no raw sulfur measurement could be obtained from either the EIA analytical file or the EIA-7A data base.

For these various reasons, 143 plants, out of a total of 323 plants that processed over 90,700 metric tons (100,000 short tons) in 1983, were excluded from consideration. Table 3.2 presents a breakdown of the total number of plants that processed over 90,700 metric tons (100,000 short tons) and the number of plants (of this total) for which S_p was calculated.

Because a sulfur tonnage could not be calculated for all of the plants in the EIA-7A data base, it was necessary to extrapolate the sulfur reduction estimates from the plants for which estimates could be made to the plants excluded from consideration, using the following equation:

Table 3.2. Plant Population and Sample Size by State

State/Region	Total # of Plants that Processed Over 90,700 Metric Tons in 1983	# of Plants Included in Sample
Alabama	17	11
Colorado	3	1
Eastern Kentucky	40	13
Illinois	24	22
Indiana	12	9
Iowa	1	1
Kansas	3	0
Maryland	1	0
Missouri	4	2
New Mexico	2	1
Ohio	19	10
Pennsylvania	62	38
Tennessee	3	2
Texas	1	0
Utah	4	4
Virginia	27	3
Washington	2	0
West Virginia	88	56
Western Kentucky	10	7
<i>Total</i>	<i>323</i>	<i>180</i>

$$SR_i = \left[\frac{\sum_{j=1}^n S_{p(j)}}{\sum_{j=1}^n C_{(j)}} \right] \left[\sum_{j=1}^m C_{(j)} \right] \quad (2)$$

where

- SR_i = total estimated tonnage of sulfur removed from all the coal cleaned by plants that processed more than 90,700 metric tons (100,000 short tons) of coal in 1983, and that are located in state i.
 $S_{p(j)}$ = S_p for plant j [see definition of S_p given for Eq. (1)].
 $C_{(j)}$ = C for plant j [see definition of C given for Eq. (1)].
 n = total number of plants located in state i for which a value for S_p was calculated.
 m = total number of plants located in state i that processed more than 90,700 metric tons (100,000 short tons) of coal in 1983.

For each state, the value for SR_i was multiplied by 2 to convert from tons of sulfur to tons of SO_2 .

Finally, to put the SO_2 reduction estimates in perspective, we estimated the total amount of SO_2 remaining in the coal cleaned in 1983, as follows:

$$SC_{(j)} = [R_{(j)}] [SR_{(j)}] - S_{p(j)} \quad (3)$$

$$SC_i = \left[\frac{\sum_{j=1}^n SC_{(j)}}{\sum_{j=1}^n C_{(j)}} \right] \left[\sum_{j=1}^m C_{(j)} \right] \quad (4)$$

where

- $SC_{(j)}$ = tons of sulfur remaining in the coal processed by plant j after coal has been cleaned.
 $R_{(j)}$ = R for plant j [see definition of R given for Eq. (1)].
 $SR_{(j)}$ = SR for plant j [see definition of SR given for Eq. (1)].
 $S_{p(j)}$ = S_p for plant j [see definition of S_p given for Eq. (1)].

SC_i	=	total estimated quantity of sulfur remaining in all the coal cleaned by plants that processed more than 90,700 metric tons (100,000 short tons) of coal in 1983 and that are located in state i.
$C(j)$	=	C for plant j [see definition of C given for Eq. (1)].
n	=	total number of plants located in state i for which a value for S_p was calculated.
m	=	total number of plants located in state i that processed more than 90,700 metric tons (100,000 short tons) of coal in 1983.

For each state, the value for SC_i was multiplied by 2 to convert from tons sulfur to tons SO_2 .

After developing the current SO_2 reduction estimates using the method described above, state-level curves showing the potential SO_2 reduction attainable at different heat content yields were derived by pressing washability data in a coal cleaning model; separate curves were developed for level 2, level 3, and level 4 cleaning. Within each state, separate curves were developed for the cleaned and uncleaned portions of the state's 1983 production. The curves are presented in Chapter 4, along with a description of the method used to derive the curves. The curves for the cleaned production were used to derive estimates of the *additional* SO_2 that could be removed through more intensive cleaning of currently cleaned coal. As a part of the estimation process, and also to check the current SO_2 reduction estimates against the potential SO_2 reduction curves, an attempt was made to locate the current SO_2 reduction estimate for each state on the state's clean coal curves. Since, within any given state, the cleaning plants do not all operate at the same preparation level and yield, to select a single point on one of the curves as "the" point at which the state's plants are operating is obviously an oversimplification. Nonetheless, through careful selection of the point, this approach enabled the development of reasonable approximations of the potential for further reductions in SO_2 through higher-intensity cleaning.

In most cases, it proved possible to locate the current SO_2 reduction estimates at reasonable points on the potential SO_2 reduction curves. However, for two regions (Pennsylvania and eastern Kentucky), the current SO_2 reduction estimate could be located only at very low heat-content yields (85 percent on the curves for the higher preparation levels -- level 3 in the case of Pennsylvania, and level 4 in the case of eastern Kentucky). In another state (Virginia), the current SO_2 reduction estimate fell outside the range of the curves. Given the problems with both the EIA-7A data used in the development of the current SO_2 reduction estimates and the washability data used to derive the potential SO_2 reduction curves, the presence of discrepancies between the estimates and the curves was not surprising. However, one of the advantages of the basic approach used in this study is that it provided a means of comparing and checking the results. Both the data sources and the methods used to develop the current SO_2 reduction estimates and the potential SO_2 reduction curves differed; therefore, the curves and estimates could be used as independent verifications of each other.

The importance of having this means of checking the results cannot be overemphasized; through the use of this means the problematic results for Virginia, eastern Kentucky, and Pennsylvania were identified and adjusted. In the case of Virginia, it was concluded that the potential SO_2 reduction curves, rather than the current SO_2 reduction estimate, were inaccurate; this conclusion is discussed in more detail in Chapter 4. However, for Pennsylvania and eastern Kentucky, the problem appeared to lie in the current SO_2 reduction estimates. Specifically, in the case of eastern

Kentucky, the current SO₂ reduction estimate (43 percent of the SO₂ contained in the raw coal input to the region's plants) was quite high compared with the estimates for other regions, and was based on a relatively small sample of plants (only 33 percent of the plants operating in the region were included in the sample). Therefore, it was decided that the current reduction estimate should be lowered. The potential SO₂ reduction curves, presented in Chapter 4, provided a means of making this adjustment: by locating a more reasonable point on the curves, a new estimate could be developed. Since eastern Kentucky appears to be relying primarily on level 2 and level 3 cleaning, the new reduction point was located on the level 3 curve.* A Btu yield of 89 percent was chosen as the yield based on the shape of the curve; this yield corresponds to an SO₂ reduction (in tons, rather than tons per million Btu) of 37 percent. By applying this percentage to the total quantity of SO₂ in the raw coal input to eastern Kentucky's plants (431,000 metric tons (475,000 short tons); see Table 3.3), a new estimated reduction of 159,000 metric tons (175,000 short tons) was derived.

In the case of Pennsylvania, the current SO₂ reduction estimate of 894,000 metric tons (985,000 short tons) represented 49 percent of the SO₂ in the raw coal; in percentage terms, the estimate for Pennsylvania was the highest of all the states. Even when allowances were made for the fact that Pennsylvania coal is highly amenable to SO₂ reduction through cleaning, a current SO₂ reduction of 49 percent seemed high. Therefore, it was decided that the current reduction estimated needed to be adjusted. A new current reduction point was located on the level 3 curve at an 85 percent yield; this point corresponds to an SO₂ reduction (in tons) of 45 percent. By applying this percentage to the total quantity of SO₂ in the raw input to the state's plants (1,838,000 metric tons (912,000 short tons)) an adjusted SO₂ reduction total of 827,000 metric tons (912,000 short tons) was obtained.

Results

Table 3.3 presents the results obtained using the methodology described in the preceding section. The first column of the table presents state-by-state estimates of the total quantity of coal cleaned (on a clean ton basis). These clean coal production estimates were derived from the cleaning data in the EIA-7A data base and represent the total quantities of clean coal produced by all large mines (mines producing more than 90,700 metric tons (100,000 short tons) per year) in 1983. The next three columns present estimates of the quantity of SO₂ in the raw coal input to cleaning plants that processed over 90,700 metric tons (100,000 short tons) in 1983, the quantity of SO₂ removed by these plants, and the quantity of SO₂ remaining in the plants' coal output.

* The original current reduction estimate could be located only on the level 4 curve. In locating the new point, the level 3 curve, rather than the level 2 curve, was selected to take into account the fact that eastern Kentucky does contain some level 4 plants (although level 2 and level 3 plants appear to predominate.)

Table 3.3. Current SO₂ Reduction Estimates (Based on 1983 Data)

Region and State	Quantity of Coal Cleaned ^a (Thousand Clean Metric Tons)	Quantity of SO ₂ in Raw Coal ^a (Thousand Metric Tons)		
		Input to Mechanical Cleaning Plants	Removed Through Mechanical Cleaning	Remaining in Clean Coal
Appalachia ^b				
Alabama	13,377	397	55	342
E. Kentucky	18,067	431	159	272
Ohio	19,317	2,175	741	1,434
Pennsylvania	29,689	1,838	827	1,011
Tennessee	1,919	81	58	23
Virginia	11,186	243	45	198
W. Virginia	62,745	2,875	943	1,932
Total	156,300	8,040	2,828	5,212
Midwest				
Illinois	43,448	3,877	1,463	2,414
Indiana	19,588	1,466	204	1,262
W. Kentucky	19,599	2,163	848	1,315
Total	82,635	7,506	2,515	4,991
West				
Colorado	1,434	27	10	17
Missouri	2,362	363	130	233
New Mexico	145	3	1	2
Utah	1,367	24	12	13
Total	5,308	417	153	265
Grand Total	244,243	15,963	5,486	10,468

^aIncludes only coal produced and SO₂ removed by operators that mined over 90,700 metric (100,000 short) tons in 1983.

^bMaryland results not included (see text).

As the data indicate, Appalachian operators cleaned more coal than their Midwestern and Western counterparts combined; of a total of approximately 245 million metric tons (270 million short tons) of as-shipped coal* produced by Appalachian operations in 1983, approximately 156 million metric tons (172 million short tons), or 64 percent, was mechanically cleaned.

The coal processed by the region's plants contained a total of 8.0 million metric tons (8.8 million short tons) of SO₂; 36 percent of this total, 2.9 million metric tons (3.2 million short tons) was removed from the coal through cleaning. Nearly all of this 2.9 million metric tons (3.2 million short tons) of SO₂ was removed from coal mined and processed in the northern part of the region. (For the purposes of this discussion, Appalachia has been divided into a northern subregion, consisting of Pennsylvania, Ohio, and West Virginia, and a southern subregion, consisting of Alabama, eastern Kentucky, Tennessee, and Virginia.)

In fact, Northern Appalachian plants accounted for 88 percent of the total SO₂ reduction. This in part reflects the fact that Northern Appalachian coal generally contains more sulfur than Southern Appalachian reserves; therefore, more SO₂ can be removed from Northern Appalachian coal. In fact, as Table 3.3 indicates, more SO₂ was removed from Ohio, Pennsylvania, and West Virginia coal than was present in the raw coal processed by southern Appalachian operators. Within Northern Appalachia, reserves in Ohio contain the most sulfur, followed by Pennsylvania and West Virginia.

The relatively high sulfur content of Northern Appalachian coal is probably one of the reasons Northern Appalachian operators clean a larger percentage of their total production than do their southern counterparts; this greater utilization of mechanical cleaning in turn contributed to the large SO₂ reduction tonnages achieved by the northern states. All three of the northern states mechanically cleaned at least 50 percent of their as-shipped tonnage; the state-by-state percentage breakdown was as follows:

- Approximately 75 percent of Ohio's total 1983 as-shipped tonnage mined by operations producing over 90,700 metric tons (100,000 short tons) was cleaned.
- Approximately 60 percent of Pennsylvania's total 1983 as-shipped tonnage mined by operations producing over 90,700 metric tons (100,000 short tons) was cleaned.
- Approximately 72 percent of West Virginia's total 1983 as-shipped tonnage mined by operations producing over 90,700 metric tons (100,000 short tons) was cleaned.

Ohio cleaned a larger percentage of its as-shipped tonnage than did either Pennsylvania or West Virginia despite the fact that, unlike Pennsylvania and West Virginia, Ohio produces little if any metallurgical coal and relies heavily on surface mining (68 percent of Ohio's total 1983 tonnage was produced by surface mines, versus 47 percent of Pennsylvania's and 20 percent of West Virginia's production). It appears that the high sulfur content of Ohio coal, relative to West

* "As-shipped" tonnage figures represent a combination of raw, crushed and screened, and mechanically cleaned coal. Coal is included in these figures in the condition (raw or clean) in which it was shipped; that is, some of the coal included in the figures is on a raw ton basis, and some is on a clean ton basis.

Virginia and Pennsylvania coal, is forcing operators to rely more heavily on mechanical cleaning to produce a marketable.

A large percentage of Northern Appalachian coal is mechanically cleaned, and with good results. Pennsylvania operators, in particular, are achieving good results; Table 3.3 reveals that washing removed 49 percent of the SO₂ in the coal input to Pennsylvania cleaning plants (compared with 34 percent for Ohio and 33 percent for West Virginia). Pennsylvania plants outperformed West Virginia plants despite the fact that Pennsylvania appears to rely more heavily on level 2 and less heavily on level 4 preparation than does West Virginia. This suggests that Pennsylvania coals may be more amenable to SO₂ reduction through washing than West Virginia coals (although no definite conclusions regarding the amenability of a coal to washing can be drawn without first analyzing washability data in detail). On the other hand, Ohio appears to rely more heavily on level 2 and less heavily on level 4 preparation than does Pennsylvania; therefore, it is possible that Ohio coals more closely resemble Pennsylvania coals, in terms of amenability to washing, than our SO₂ reduction estimates would indicate.

Southern Appalachian coal contains less sulfur than Northern Appalachia's reserves; eastern Kentucky and Virginia, in particular, contain large quantities of high-quality coal. As a result, it appears that operators in Southern Appalachia are under less pressure to wash their coal. The following are the estimated percentages of the as-shipped 1983 total tonnages that were mechanically cleaned, for each Southern Appalachian state:

- Alabama - 69 percent
- Eastern Kentucky - 46 percent
- Tennessee - 65 percent
- Virginia - 64 percent

Oddly, although Alabama led the Southern Appalachian region in mechanical cleaning, it is the only Southern Appalachian state in which underground mining yields less than 50 percent of total production. This makes sense only when one recalls that Alabama produces a significant amount of metallurgical coal (and perhaps more importantly, that the other Southern Appalachian states also produce significant amounts of metallurgical coal) and that Alabama's reserves contain more sulfur than eastern Kentucky's and Virginia's reserves (although not Tennessee's reserves). Eastern Kentucky relies less on underground mining than does either Virginia or Tennessee (53 percent of eastern Kentucky's total 1983 production was produced by underground mines, as compared with 78 percent of Virginia's and 66 percent of Tennessee's production); this may help to explain why eastern Kentucky washed a smaller percentage of its as-shipped tonnage than did either Tennessee or Virginia.

Two of the factors contributing to the relatively low SO₂ reduction levels characterizing the Southern Appalachian states are that Southern Appalachia's reserves are relatively low in sulfur and that Southern Appalachian operators wash a smaller percentage of their product than do their Northern Appalachian counterparts. There is, however, another important factor: the plants in some of the Southern Appalachian states (specifically Virginia and Alabama) are not attaining good SO₂ reduction results. According to Table 3.3, in 1983, Virginia's plants removed only 19 percent of the SO₂ contained in the coal they processed; Alabama's plants performed even worse

-- removing only 14 percent. Yet both Alabama and Virginia operators appear to rely more heavily on level 3 and 4 preparation than on level 2 preparation. Thus, it is possible that Virginia and Alabama coals are simply not very amenable to SO₂ reduction through washing.

To summarize the results for the Appalachian region, most of the SO₂ removed through preparation was removed from coal mined and processed in Pennsylvania, Ohio, and West Virginia. All of these Northern Appalachian states (particularly Pennsylvania) are achieving good SO₂ reduction results through cleaning; thus, Northern Appalachia may represent an area in which significant increases in the tonnage of SO₂ removed through preparation could be effected through increased utilization of mechanical cleaning. In general, the same is not the case for Southern Appalachia (even though Southern Appalachia is washing a smaller percentage of its production than is Northern Appalachia), because the sulfur content of Southern Appalachian coal is quite low, and it appears that, at least in Virginia and Alabama, the coal may not be as amenable to sulfur reduction through washing as is Northern Appalachian coal. Within Southern Appalachia, only the unwashed coal of eastern Kentucky contains a relatively large quantity of SO₂ that is potentially removable through cleaning. (Tennessee, unlike eastern Kentucky, produced only a small quantity of coal per year; thus, the amount of SO₂ that could be removed by washing Tennessee's coal is relatively insignificant.)

Although the Midwest cleaned less coal than Appalachia in absolute terms (82,635,000 clean metric tons (91,089,000 clean short tons) versus 156,300,000 clean metric tons (172,700,000 clean short tons) for Appalachia -- see Table 3.3), in relative terms it cleaned a larger percentage of its as-shipped production (76 percent, versus 64 percent for Appalachia). As Table 3.3 indicates, the coal processed by the region's plants contained 7,506,000 metric tons (8,274,000 short tons) of SO₂; of this total, 2,515,000 metric tons (2,773,000 short tons) (34 percent) was removed through cleaning.

These sulfur and sulfur reduction quantities are not much lower than the corresponding quantities for Appalachia (see Table 3.3), despite the fact that Appalachia cleaned nearly twice as much coal as the Midwest. This indicates that Midwestern coal contains much more sulfur than does Appalachian coal, a situation that appears to have forced Midwestern operators to rely more heavily on mechanical cleaning. In fact, of all the mining regions, only the Midwest is cleaning as large a percentage of its surface as of its underground production; thus, it appears that sulfur rather than ash reduction may be the primary objective of Midwestern preparation plant operators.

On a state-by-state basis, the estimated percentages of the as-shipped 1983 tonnages that were mechanically cleaned are as follows:

- Illinois - 85 percent
- Indiana - 71 percent
- Western Kentucky - 64 percent

Illinois's heavy reliance on mechanical cleaning has helped to make it the nation's leading state in SO₂ reduction; West Virginia, its closest rival, trailed Illinois by 520,000 metric tons (574,000 short tons) of SO₂ in 1983 (see Table 3.3). Another factor in Illinois's SO₂ reduction success is the relatively good results being achieved by the state's preparation plants. Of the 3.9 million

metric tons (4.3 million short tons) of SO₂ in the raw coal processed by Illinois plants in 1983, 38 percent (1.5 million metric tons (1.6 million short tons)) was removed. This compares favorably with the SO₂ reduction levels attained at most Appalachian plants, even though Illinois operators appear to rely more heavily on level 2 and less heavily on level 4 preparation. Unfortunately, because Illinois operators are already washing most of their coal, the potential for removing significant quantities of SO₂ beyond that already being removed is probably not great.

Like Illinois coal, western Kentucky coal appears relatively amenable to SO₂ reduction through washing. In 1983, the raw coal processed by western Kentucky's plants contained a total of 2.2 million metric tons (2.4 million short tons) of SO₂, of which 39 percent (848,000 metric tons (935,000 short tons)) was removed through cleaning. Indiana's preparation plants, on the other hand, removed only 204,000 metric tons (225,000 short tons) of SO₂ from the coal through cleaning (versus 848,000 metric tons (935,000 short tons) of SO₂ for western Kentucky operators). This represents only 14 percent of the SO₂ in the raw coal processed by Indiana's plants. Since most of Indiana's plants are level 3 plants, it is possible that the state's operators could improve SO₂ reduction by switching from level 3 to level 4 preparation.

In addition to presenting SO₂ reduction estimates for the major Appalachian and Midwestern coal-producing states, Table 3.3 also provides estimates for those Western states for which usable EIA-7A data were available. Four Western states are included in the table; one of these is characterized by high-sulfur reserves (Missouri), and three are characterized by low-sulfur coal (Colorado, New Mexico, and Utah). Missouri cleaned over 50 percent of its 1983 as-shipped tonnage, and its plants succeeded in removing 130 metric tons (143 short tons) of SO₂ from the coal they processed.

Although Missouri's high-sulfur coal appears to be amenable to SO₂ reduction through washing, the state does not produce much coal; thus any SO₂ reduction gains made by subjecting these states' unwashed production to cleaning would be small in absolute terms. Colorado, New Mexico, and Utah, on the other hand, produce significant quantities of coal, most of which is unwashed. Furthermore, these states appear to be achieving fairly good SO₂ reduction results through washing; Utah's plants, for example, removed 48 percent of the SO₂ from the coal they cleaned, while Colorado's plants removed 37 percent, and New Mexico's plants removed 33 percent. However, because these states' reserves are very low in sulfur, the total quantity of SO₂ that is currently being (and might potentially be) removed from the states' production is small in absolute terms (a mere 23 metric tons (25 short tons) in 1983).

The SO₂ reduction estimates presented in Table 3.3 correspond to *all* coal produced by operations that mined over 90,700 metric tons (100,000 short tons) in 1983, regardless of the coal's end use. In Table 3.4, separate SO₂ reduction estimates are presented specifically for that portion of the 1983 production that was consumed by electric utilities. The method used to derive these utility coal estimates was essentially the same as that documented in the preceding section, except it was applied only to coal that was shipped to power plants. This was possible because the EIA-7A (Supplement) data base includes data on the quantity of coal shipped by each operation to each of 6 "consumer categories"; one of the consumer categories is identified as "electric utilities."

The last column of Table 3.4 shows, for each state, the percentage of the SO₂ in the raw utility coal that was removed through cleaning. For comparative purposes, the second to last column

**Table 3.4. Current SO₂ Reduction Estimates for Utility Coal Only
(Based on 1983 Data)**

Region State	Utility Coal Cleaned ^a (Thousand Clean Metric Tons)	Quantity of SO ₂ in Raw Utility Coal ^a (Thousand Clean Metric Tons)			% of Total SO ₂ in Raw Coal Removed Through Cleaning	
		Input to	Removed	Remain-	All	Utility
		Mech. Clea- ning Plants	Through Mech. Cleaning	ning in Clean Coal		
Appalachia						
Alabama	8,312	250	7	243	14	3
E. Kentucky	10,920	354	136	218	43	38
Ohio	18,042	2,039	692	1,347	34	34
Pennsylvania	17,104	1,046	420	626	49	40
Tennessee	1,646	73	51	22	72	70
Virginia	3,533	81	31	50	19	38
W. Virginia	38,933	2,453	667	1,786	33	27
Total	98,490	6,296	2,004	4,292	36	32
Midwest						
Illinois	37,170	3,409	1,312	2,097	38	38
Indiana	18,613	1,390	188	1,202	14	14
W. Kentucky	18,317	2,032	801	1,231	39	39
Total	74,100	6,831	2,301	4,530	34	34
West						
Missouri	2,339	359	128	231	36	36
Utah	786	16	8	8	50	50
Total	3,125	375	136	239	37	36
Grand Total ^b	175,715	13,502	4,441	9,061	35	33

^aIncludes only utility coal and SO₂ produced by operations that mined over 90,700 metric tons in 1983.

^bColorado and New Mexico are not included here because the coal cleaned in these states in 1983 was not utility coal.

presents the corresponding percentages for *all* (utility plus non-utility) coal. As can be seen the percentages for the utility production are generally fairly similar to the percentages for the total production. However, in some cases the difference between the two percentages is significant. As would be expected, the significant differences occur in states that are producing large amounts of non-utility coal (e.g. Pennsylvania, West Virginia, and Alabama). Furthermore, where significant differences occur, the percentage of SO₂ removed for utility coal is typically lower than the percentage for all coal. This reflects the fact that a large percentage of non-utility production is used to produce coke; coking coal is generally subjected to more intensive cleaning than utility

coal. The SO₂ reduction percentage for utility coal was higher than the percentage for all coal in only two states: Virginia and Iowa. It is believed that this is due to inadequate sample sizes in these states; Table 3.1 indicates that the sample included only 1 plant in Iowa and 3 in Virginia.

Results Compared with Previous EPA Studies

At least one other published study performed for EPA, in addition to the present study, has attempted to estimate current SO₂ reduction levels. This study, performed by Teknekron,⁴ yielded estimates of the quantity of SO₂ removed from all coal shipped to electric utilities in 1979 for the following eight states: Pennsylvania, Ohio, West Virginia (broken down into northern and southern halves), Virginia, Kentucky (broken down into eastern and western halves), Indiana, Illinois, and Alabama. Teknekron developed its estimates by distributing the USBM washability data base to 1979 clean coal utility deliveries originating in the eight states, and then using the distributed data to estimate the quantity of SO₂ removed from the deliveries.

Because the use of the washability data requires a specification of the topsize of the coal and the specific gravity of separation, Teknekron assumed that all the coal was crushed to a 3.81-centimeter (1.5-inch) topsize and was washed at a specific gravity of separation of 1.6.

Although the results of the Teknekron study do not correspond precisely with the results presented in Table 3.4 (since our results apply to the utility coal production for 1983 as opposed to 1979), the differences between the two sets of SO₂ reduction estimates should not be too large, especially when the estimates are normalized on the basis of the total clean coal tonnages to which they correspond. Thus, it was felt that comparing the two sets of results would be valid and useful. Aggregating Teknekron's results to the regional levels employed in Table 3.4, and normalizing the two sets of results by the total clean coal tonnages, yielded the regional SO₂ reduction values shown in Table 3.5.

Both the absolute and the normalized SO₂ reduction estimates of this study fell on the high side of Teknekron's estimates. Because the methods used in the two studies differed significantly, it is not surprising that the results of the studies differed. The differences between SAIC's results and Teknekron's can perhaps be explained by the fact that Teknekron's estimates rest on the assumption that all coal is washed by one-circuit (i.e., level 2) preparation; because level 3 and level 4 preparation plants were included in our sample of 180 operating plants, one would expect the estimates here to be systematically higher than Teknekron's (as is the case).

Table 3.5. Teknekron and SAIC Estimates of SO₂ Reduction

	SO ₂ Removed, Metric Tons (Short Tons)	SO ₂ Removed per Ton of Coal Cleaned
Teknekron		
Appalachia ^a	444,521 (490,000)	0.010
Midwest	1,106,765 (1,220,000)	0.020
SAIC		
Appalachia ^b	2,921,000 (3,220,000)	0.019
Midwest	2,525,000 (2,773,000)	0.030

^aExcluding Maryland and Tennessee.

^bIncluding Tennessee and excluding Maryland.

4. Potential SO₂ Reduction

Methodology

The methodology used to develop estimates of the potential for improving current SO₂ reduction levels was considerably more complex than that used to develop the current reduction estimates. Each of the four major steps constituting the methodology will be discussed in detail, but first, a general overview of the approach to the problem is in order.

Figure 4.1 illustrates the general methodology. Step 1 involved modifying Skea and Rubin's coal preparation simulation model,⁵ translating the modified version of the model into a series of SAS and FORTRAN programs, and using the programs to process a data base consisting of the results of washability tests performed on over a thousand coal samples taken from mines located throughout the country. For each sample, the model generated estimates of the SO₂ that could be removed from the coal through washing, and the costs associated with this SO₂ removal, for a variety of preparation plant operating conditions. The various operating conditions were chosen to be representative of the range of operating practices now in commercial use.

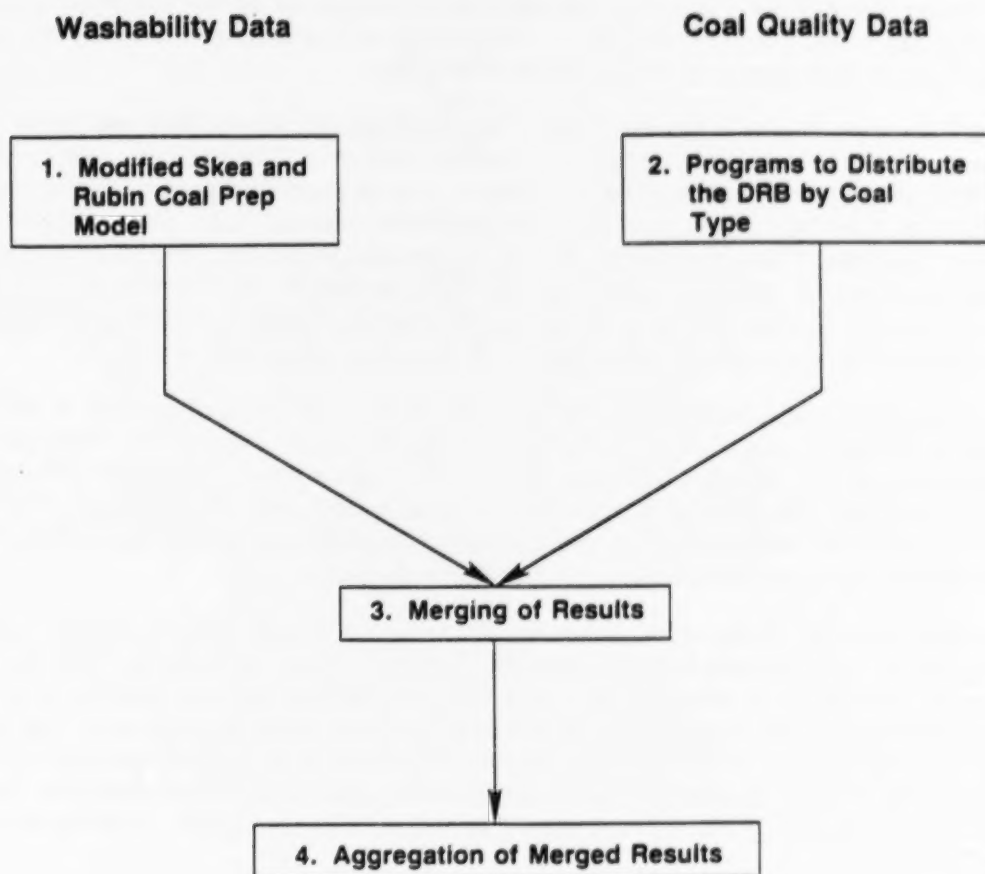
In all, 18 separate model runs were made for each of the possible combinations of the three mechanical cleaning levels (2, 3, and 4) and six different values of Btu yield. Thus, for each washability sample, 18 different SO₂ reduction and cost estimates were developed, covering the range of technically and economically feasible cleaning options available at present. The exact form of the estimates, and the specific combinations of preparation level and Btu yield to which they correspond, will be presented and discussed in this chapter.

The modified Skea and Rubin model generates SO₂ reduction and preparation cost estimates for each *sample of coal* included in the washability data base; what was needed, however, were estimates of potential SO₂ reduction and costs for each *block of reserves* included in the U.S. Demonstrated Reserve Base (DRB).² Thus, it was necessary to extrapolate the results generated for each individual sample to the reserves represented by the sample. This task was accomplished in the third step of our methodological approach; however, before the extrapolation from samples to reserves could be carried out, it was necessary to perform some preliminary development work on the DRB.

Specifically, it was necessary to characterize the reserves included in the DRB as to their run-of-mine quality. This was accomplished by merging the DRB (disaggregated to the bed/county level) with a coal quality data base containing the results of laboratory analyses of coal samples taken from mines and drill holes located throughout the country. Each of the analyses included in the data base was assigned that portion of the reserve base determined to be most closely represented by the analysis; after distributing the entire DRB to the quality analyses, each separate block of reserves was assigned a raw coal type based on the Btu and sulfur content values for the analysis to which the reserve block had been assigned.

Thus, the output from this, the second step in the development of potential SO₂ reduction estimates, was a DRB divided into small (sub-bed/county level) blocks of reserves, each assigned

Figure 4.1. General Methodology Used for Developing Estimates of Potential SO₂ Reduction



a coal type representative of its raw Btu and sulfur content. It should be noted that the coal quality data base used in step 2 includes raw coal analyses derived from the washability data used as input to the modified Skea and Rubin model; however, the vast majority of the approximately 33,000 raw analyses constituting the quality data base were obtained from the EIA/U.S. Bureau of Mines analytical file.

Once the DRB was characterized as to raw coal quality, it was possible to merge the reserve base with the results generated by the modified Skea and Rubin model. The procedure used to accomplish this task was very similar to the method used to distribute the DRB to coal type: each block of reserves included in the DRB was assigned to the washability sample determined to be most closely representative of the reserve block; the potential SO₂ reduction and preparation cost estimates developed for the sample were then simply assigned to the corresponding reserve block. Thus, the output from the first three steps was a DRB subdivided into small reserve blocks, each containing the following information:

- A raw coal type.
- A range of estimates of the percentage reduction in raw SO₂ content attainable by cleaning the coal contained in the reserve block.
- Estimates of the costs that would be incurred in achieving the estimated reduction levels.

Given that the washability data include analyses of the raw quality of each sample, it would certainly have been possible to extrapolate the raw Btu and sulfur content of each washability sample to its assigned reserve block at the same time that the SO₂ reduction and cost estimates were extrapolated from the samples to the reserves. However, although this approach would have eliminated the need for step 2 in the overall methodology, it would also have forced sole reliance on the washability data to assign raw coal types to the reserves. As was noted previously, the raw coal analyses contained in the washability data base constitute only a small fraction of the quality data available. Therefore, to ensure that the assignment of raw coal types would be as accurate as possible, it was necessary to incorporate quality data from sources other than the washability data base; this in turn necessitated the inclusion of an additional step (step 2) in the methodology.

As stated above, the output from the third step of our procedure consisted of a reserve base subdivided into *small* reserve blocks; in fact, the individual blocks were smaller than the bed/county level reserve blocks that were used as input to the step 2 procedure. Given that the step 3 output consisted of over 50,000 such blocks, it is clear that this output did not submit to easy analysis. Thus, it was necessary to aggregate the step 3 output to obtain useful, analyzable results. One of the main benefits derived from the chosen approach to the problem was that it yielded, as the output from step 3, a highly disaggregated, flexible reserve data base (characterized as to raw coal quality and potential SO₂ reduction) that can be aggregated in a myriad of different ways (e.g., to the bed/county level, county level, bed/state level, etc.). In step 4, the reserve data base was first aggregated (and SO₂ reduction estimates) to the bed/county level, and then the results were used to derive state-level SO₂ reduction and preparation cost estimates corresponding to that portion of the 1983 raw coal production that was cleaned. These estimates are presented later in this chapter, in the section titled "results." It should be noted that the program used to derive the estimates can, with relatively minor modifications, be used to aggregate the step 3 output to levels other than that chosen for this report.

Step 1:
The Modified Skea and Rubin
Coal Preparation Model

With the preceding general overview of the methodological approach serving as background, the following subsections provide a detailed description of each of the four main steps identified above. The first step, as discussed above (see Figure 4.1), involved the modification of the Skea and Rubin model⁵ and the use of the modified model to develop a range of potential SO₂ reduction estimates and preparation costs for each washability sample included in the new washability data base. Separate SO₂ reduction and cost estimates were developed for 18 different combinations of preparation level and Btu yield; the specific combinations used (along with the exact form of the cost and reduction estimates output by the model) are indicated in Table 4.1. This table is representative, in all essential details, of the general form of the output generated by the model; a similar table was output for each of the samples included in the washability data base.

How were these tables generated? A number of tasks were involved, including:

- Locating and collecting washability data.
- Entering the data on the computer and checking the data for entry errors.
- Modifying the Skea and Rubin model.
- Translating the model into computer programs.
- Running the programs.

These tasks fall into two main groups: those associated with developing the input data for the model and those involving model development.

Data Development Tasks. Most (if not all) computer models designed to simulate the mechanical cleaning of coal require as input data on the washability characteristics of the coal; the Skea and Rubin model is no exception. Why are washability data important? To answer this question, it is necessary to consider, briefly, the general theory behind coal preparation.

The basic purpose of coal preparation is to separate and remove impurities from run-of-mine coal. With only one exception, all of the mechanical cleaning processes in commercial use today rely on differences in the specific gravity of coal and its associated impurities to effect the required separation. The exception is the froth flotation process, which takes advantage of the hydrophobic tendencies of coal and the hydrophilic tendencies of its associated impurities, to separate the two. Because the principle upon which froth flotation is based differs from the specific gravity principle used in the other commercial preparation processes, the Skea and Rubin model cannot simulate the froth flotation process. Fortunately, only a small percentage of coal is cleaned using the froth flotation technique.

Processes other than froth flotation are based on the fact that the specific gravity of coal is less than the specific gravity of its associated impurities (including pyritic sulfur); by exploiting this

Table 4.1. General Form of the Output Generated by the Modified SKEA and Rubin Model

	Preparation Level		
	2	3	4
Btu Yield	95%	95%	95%
Potential SO ₂ Reduction	S2,95	S3,95	S4,95
Operating Costs	O2,95	O3,95	O4,95
Capital Costs (New Plants)	C2,95	C3,95	C4,95
Capital Costs (Upgrading Existing Plants)	U2,95	U3,95	U4,95
Weight Yield	Y2,95	Y3,95	Y4,95
Btu Yield	90%	90%	90%
Potential SO ₂ Reduction	S2,90	S3,90	S4,90
Operating Costs	O2,90	O3,90	O4,90
Capital Costs (New Plants)	C2,90	C3,90	C4,90
Capital Costs (Upgrading Existing Plants)	U2,90	U3,90	U4,90
Weight Yield	Y2,90	Y3,90	Y4,90
Btu Yield	85%	85%	85%
Potential SO ₂ Reduction	S2,85	S3,85	S4,85
Operating Costs	O2,85	O3,85	O4,85
Capital Costs (New Plants)	C2,85	C3,85	C4,85
Capital Costs (Upgrading Existing Plants)	U2,85	U3,85	U4,85
Weight Yield	Y2,85	Y3,85	Y4,85
Btu Yield	80%	80%	80%
Potential SO ₂ Reduction	S2,80	S3,80	S4,80
Operating Costs	O2,80	O3,80	O4,80
Capital Costs (New Plants)	C2,80	C3,80	C4,80
Capital Costs (Upgrading Existing Plants)	U2,80	U3,80	U4,80
Weight Yield	Y2,80	Y3,80	Y4,80
Btu Yield	75%	75%	75%
Potential SO ₂ Reduction	S2,75	S3,75	S4,75
Operating Costs	O2,75	O3,75	O4,75
Capital Costs (New Plants)	C2,75	C3,75	C4,75
Capital Costs (Upgrading Existing Plants)	U2,75	U3,75	U4,75
Weight Yield	Y2,75	Y3,75	Y4,75

(continued)

Table 4.1. General Form of the Output Generated by the Modified SKEA and Rubin Model (Cont'd.)

	Preparation Level		
	2	3	4
Btu Yield	70%	70%	70%
Potential SO ₂ Reduction	S _{2,70}	S _{3,70}	S _{4,70}
Operating Costs	O _{2,70}	O _{3,70}	O _{4,70}
Capital Costs (New Plants)	C _{2,70}	C _{3,70}	C _{4,70}
Capital Costs (Upgrading Existing Plants)	U _{2,70}	U _{3,70}	U _{4,70}
Weight Yield	Y _{2,70}	Y _{3,70}	Y _{4,70}

$S_{i,j}$ = Fraction of SO₂ remaining in the coal after cleaning at preparation level i, Btu yield j.

$O_{i,j}$ = Annual operating costs (in dollars per clean ton) for operating preparation plant at level i, Btu yield j.

$C_{i,j}$ = Annualized capital costs (in dollars per clean ton) for building a new preparation plant to be operated at level i, Btu yield j.

$U_{i,j}$ = Annualized capital costs (in dollars per clean ton) for purchasing and installing the cleaning equipment for a plant to be operated at level i, Btu yield j.

Y = Weight yield of product after cleaning at preparation level i, Btu yield j.

difference, the two can be separated. However, a perfect separation is not attainable. Some mineral matter will remain in the clean coal following preparation, and some combustible material will be misplaced to the refuse. The degree to which the separation falls short of perfection is dependent on the raw and clean coal qualities, the prep plant operating conditions, and the washability of the coal. Coal washability can be roughly defined as the ease with which a coal can be separated from its associated impurities.

Any given raw coal feed consists of particles combining coal and impurities in various proportions; thus, the particles cover a wide spectrum of specific gravities. The washability of a coal defines this spectrum; washability data consist of the percentage (or cumulative percentage), by weight, of the raw coal falling in contiguous specific gravity intervals and the quality (Btu, sulfur, and ash contents) of each specific gravity fraction. Because coal crushing can help to "liberate" coal from impurities by breaking down large particles into smaller, purer particles, the washability of a given coal varies with the particle size range to which the coal has been crushed. Thus, the washability data of a given coal are presented for different size ranges of the coal.

Table 4.2 is an example of washability data for a sample of coal from the Upper Freeport seam in Butler County, Pennsylvania. As can be seen, the data are subdivided into three groups representing three size ranges of coal particles: 1-1/2 inch x 100 mesh, 3/8 inch x 100 mesh, and 14 mesh x 0. Within each size category, the percentages of the raw coal with specific gravities less than 1.3, 1.4, 1.5, 1.6, and 1.8 are given. Also, the Btu/lb, percent ash by weight, percent

Table 4.2. Sample Washability Data, Upper Freeport Seam, Butler County, Pennsylvania

Fraction by Size	% Recovery by Weight in Float Coal	Btu/Lb in Float Coal	% Ash in Float Coal	% Pyritic Sulfur in Float Coal	% Total Sulfur in Float Coal
1-1/2" x 10 Mesh					
Float-1.30	44.6	14,574	3.3	0.16	0.55
Float-1.40	75.2	14,181	5.6	0.49	0.83
Float-1.60	84.4	13,864	7.4	0.81	1.18
<i>Total</i>	<i>100.0</i>	<i>12,711</i>	<i>14.1</i>	<i>1.70</i>	<i>2.04</i>
3/8" x 100 Mesh					
Float-1.30	53.8	14,611	3.1	0.06	0.47
Float-1.40	75.8	14,311	4.9	0.13	0.52
Float-1.60	84.3	13,957	7.0	0.26	0.63
<i>Total</i>	<i>100.0</i>	<i>12,608</i>	<i>14.7</i>	<i>1.75</i>	<i>2.09</i>
14 Mesh x 0					
Float-1.30	56.2	14,644	2.9	0.05	0.47
Float-1.40	74.6	14,411	4.3	0.07	0.48
Float-1.60	83.8	14,113	6.1	0.09	0.49
<i>Total</i>	<i>100.0</i>	<i>12,664</i>	<i>14.3</i>	<i>1.79</i>	<i>2.23</i>

Source: U.S. Department of Energy washability data tape.

pyritic sulfur by weight, and percent total sulfur by weight corresponding to each specific gravity fraction are given.

Washability data are developed empirically. Samples of the desired coal are collected and randomly split into "sub-samples." Each of the different sub-samples is then crushed to different top sizes and immersed in liquids (called "baths") with accuracy defined specific gravities. The float coal (and sink material) at each specific gravity is analyzed to determine the percent of total that the float material represents and the float coal quality.

Laboratory washability tests are conducted using heavy organic liquids or solutions of calcium chloride (possessing definite, precise specific gravities) as the separating medium. Commercial preparation plants effect a coal/impurities separation by employing various techniques (including suspensions of ground solids in water) to simulate the heavy liquid media used in the laboratory. Thus, the behavior of a coal sample in a laboratory bath, as measured during washability tests, provides a good indication of how the coal will behave in a commercial preparation plant. In other words, washability data like those presented in Table 4.2 can be (and are) used to estimate the yield and clean coal quality for a given coal washed at a given (simulated) specific gravity of separation. For example, if 1-1/2 inch x 100 mesh Lower Kittanning coal from Cambria County is to be washed at a specific gravity of separation of 1.4, it can be predicted, from Table 3.4 in

Chapter 3, that the likely yield will be about 75.2 percent and the clean coal will have a heat value of about 14,181 Btu/lb, an ash content of 5.6 percent, and a sulfur content of 0.83 percent.

Alternatively, if it is required that the yield for this same coal be 75 percent, then we can determine (again from Table 4.2) that the coal must be cleaned at a specific gravity of separation of 1.4, and that the clean coal will have the same (theoretical) quality characteristics as specified above. In a similar (though necessarily more complex) manner, the Skea and Rubin model uses washability data to predict sulfur reduction levels for specified yield constraints.

Given the model's need for washability data, our first task was to identify possible data sources. A number of such sources were identified, including:

- The U.S. Department of Energy's (DOE's) Pittsburgh Energy Technology Center
- A series of U.S. Bureau of Mines (USBM or BOM) Reports of Investigations (published from the late 1940s through the early 1970s)¹
- The Pennsylvania State University
- The Ohio Geological Survey⁶
- The Illinois State Geological Survey⁷
- The Electric Power Research Institute⁸

The data from each of these sources were subjected to a detailed examination of each of their components to ensure the development of a consistent overall data base. As expected, the majority of the useful/useable washability data came from the DOE and USBM data sources. Fortunately, the DOE database (which was obtained on computer tape) is by far the largest and most comprehensive compilation of washability test results available. It includes data for approximately 1000 samples, representing most of the major coal seams located throughout the country.

Furthermore, the data are relatively "clean." All of the tests were performed according to a standardized procedure; thus, the data are internally consistent. Each sample was subdivided (randomly) into three separate fractions for testing purposes, and each fraction was crushed to a different top size: 1-1/2 inches, 3/8 inches, and 14 mesh. Although the size fractions handled by coarse, medium, and fine-sized cleaning circuits vary from plant to plant, the washability data topsizes are fairly typical of those used in commercial cleaning. Thus, by using these topsizes as the cleaning circuit size bounds for the modified Skea and Rubin model, it was possible to avoid having to adjust the data to conform to the topsize assumptions specified for the model runs (although, as will be discussed later, a size adjustment was still necessary because the washability data are in cumulative form with respect to size).

In addition to being consistent both internally and with actual operating practice, the DOE data are relatively complete. With only a few exceptions, the test results for each sample included all the necessary yield, coal quality, and specific gravity data for each of the three size fractions. However, there was one significant problem with regard to the completeness of the DOE data. The Skea and Rubin model⁵ requires, in addition to the yield, quality, and specific gravity information, data on the percentage breakdown (by weight) of the coal into coarse, medium, and

fine-sized fractions. This information is needed in order to determine the percentages of the raw coal input to plant that will (after crushing to a 1-1/2 inch topline) be passed through each of the separate cleaning circuits. Although the DOE data base does, for some samples, provide data on the percentages of the sample (crushed to a 1-1/2 inch topline) falling in the 1-1/2 to 3/8, 3/8 to 14 mesh, 14 mesh to 100 mesh, and 100 mesh to 0 particle size ranges, for many samples these data are missing. To estimate the percentage breakdown for those samples lacking the needed data, the following approach was employed. For each bed/county combination for which samples with the required data were available, an "overall average" breakdown by size range was developed using the following equation:

$$F_{i,x,j} = \left(\sum_{K=1}^n f_{i,x,j} \right) / n$$

where

- $F_{i,x,j}$ = estimated "overall average" fraction of the bed/county combination coal falling in the size range bounded by i and j
- $f_{i,x,j}$ = fraction of sample k falling in the size range bounded by i and j
- n = total number of samples with the required data representing the bed/county combination.

For each bed/county combination, separate values of $F_{i,x,j}$ were calculated for each of the four size ranges (1-1/2 inch x 3/8 inch, 3/8 inch x 14 mesh, 14 mesh x 100 mesh and 100 mesh x 0); these values were then taken as representing the fractional size breakdown for all samples in the bed/county combination for which data were lacking. Since many samples lacking data fell in bed/county combinations for which no size fraction breakdown data were available, the process had to be repeated at the county level for these samples. Even at this level, data were not always available; repetition of the procedure at the bed/state and, finally, state levels was required in order to develop estimated breakdowns for all samples lacking data.

Once the size fraction breakdowns were developed, the DOE data were ready for input into the Skea and Rubin model. Preparation of the USBM data for use in the model required more effort. These data were obtained from the 39 Reports of Investigations mentioned earlier. Each of these reports presents the results of washability tests performed on samples taken from a single county; thus, a total of 39 counties, all of which are located in Appalachia, are covered. Unfortunately, neither the testing procedure nor the publishing procedure remained consistent across all the reports; furthermore, in many cases crucial data were either not obtained during the tests or not

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published. For example, when the sulfur content of the raw coal was low (less than 1.25 percent), the float coal was analyzed for ash but not sulfur content. Obviously, the data for these tests could not be used. Also, although the ranges for the size fractions corresponded closely to those in the DOE data base (i.e., 1/12 inch x 100 mesh, 3/8 inch x 100 mesh, 14 mesh x 0),* the fine-sized fraction (14 mesh x 0) was not always tested. Again, the data for these incomplete tests were not usable.

Even when all the size fractions were subjected to float-sink tests, the results for the fine and mid-sized fractions were not published when either:

- The coarse-coal float-sink test results indicated that the coarse coal's sulfur content could be easily reduced below 1.25 percent through washing, or
- There was little difference in the test results for the different size fractions.

Usually (but not always) the text of the report indicated which of these conditions applied. When results were not published for the first reason, the data could not be used; however, when the text indicated that the second condition held true, the coarse coal data were used as estimates of the unpublished mid- and fine-sized data. In this way it was possible to use some of the incomplete data; nonetheless, most of the data proved unusable for the various reasons cited above. All totaled, data for approximately 100 samples were usable.

Even these usable data were incomplete; two required data elements were missing. First, data on the percentage breakdown of the coal by size fraction were not available for any of the USBM samples. Fortunately, the needed percentages could be estimated using the same procedure applied to those DOE samples that also lacked size breakdown data. However, the second missing data element presented a larger problem. None of the Bureau of Mines data included information on the heating value of the raw and float coal. Although the modified version of the Skea and Rubin model does not require Btu content data as input, it does, as a minimum, require Btu yield estimates for the USBM samples. In reviewing the DOE data it was found that the Btu content of each sample, in Btu per pound ash-free, remained relatively constant over the different size fractions and specific gravities of separation. Assuming that the Btu content, on an ash-free basis, does not vary with the specific gravity of separation, the Btu yield can be calculated using the following equation:

$$B_{g,s} = \{W_{g,s} - (W_{g,s})(A_{g,s})\} (X_{g,s})(100\%) / (1 - A_{r,s}) X_{r,s}$$

where

$B_{g,s}$ = Btu yield for size fraction s (where $s=1-1/2 \times 100$ mesh, $3/8 \times 100$ mesh, etc.) and specific gravity of separation g

$W_{g,s}$ = weight yield for size fraction s and specific gravity of separation g

* In some cases, the bottom size for the fine coal fraction was 100 mesh, and the bottom size for the two coarser fractions was 0. Since the percentage of a 1-1/2 inch topsize coal that falls in the 100 mesh x 0 fraction is very small, these differences were judged to be insignificant and the USBM data were assumed to conform to the same size ranges as the DOE data.

$A_{g,s}$	=	ash content (in pounds ash per pound of coal) of the float coal at size fraction s and specific gravity of separation g
$A_{g,r}$	=	ash content (in pounds ash per pound of coal) of the raw coal
$A_{r,s}$	=	Btu content (in Btu per pound ash-free coal) of the raw float coal at size fraction s and specific gravity of separation g
$X_{r,s}$	=	Btu content (in Btu per pound ash-free coal) of the raw coal.

Since, assuming that the ash-free Btu content remains constant, $X_{g,s}$ equals and therefore cancels $X_{r,s}$, the equation can be solved using only the data provided by the USBM reports. However, although our limited review of the DOE data indicated that $X_{g,s}$ and $X_{r,s}$ were, in all cases, approximately equal, they were not exactly equal. To determine what effect this would have on the accuracy of the Btu yield estimates calculated using the equation, a test was run using the DOE data. For each specific gravity of separation, within each size fraction and DOE sample, the equation to estimate the Btu yield was used. These estimates were then subtracted from the corresponding observed Btu yield, and the arithmetic average and standard deviation of the differences were calculated for each Appalachian state* and size fraction. The results are presented in Table 4.3. As the table indicates, the differences between the estimated and actual Btu yields never exceed 1 percent for the Appalachian region covered by the USBM data. However, the table also shows that the estimated yields were consistently lower than the actual yields (hence none of the means are negative). Thus, it was decided that, while accurate estimates of Btu yield could be developed for the USBM data, these estimates would have to be adjusted to account for their consistent downward trends. The adjustment was accomplished simply by adding the appropriate mean value from Table 4.3 to each estimated yield. The standard deviations presented in the table provide some indication of the "typical" error associated with these adjusted estimates.

Besides estimating Btu yield and percentage size breakdown values for the USBM data, it was also necessary to enter these data into the computer. After data entry, a series of error check programs were run to identify keying errors and other data problems.

Model Development Tasks. Skea and Rubin, the developers of the model used as the basis for this study,⁵ are actually responsible for the development of *two* separate coal preparation models. One, a regression model, is used as the coal cleaning component for the EPA's Advanced Utility Simulation Model (AUSM).⁹ The other, an engineering/economic model, was employed to generate the data used in the development of the equations that constitute the regression model. Only the engineering/economic model was used to generate the results presented in this report. To understand why Skea and Rubin developed two models, and why only one of these models was used, the basic purpose of each model, and its relationship to the others, needs to be considered.

Skea and Rubin had as their basic objective the development of a coal cleaning component, for use in the AUSM, that could predict the yield and costs associated with cleaning the various coals

* The Bureau of Mines data did not cover any states outside of Appalachia; therefore there was no need to test the DOE data for non-Appalachian states.

Table 4.3. Means and Standard Deviations of the Differences Between Estimated and Actual Btu Yields

State and Size Fraction ^a	Mean (Percent)	Standard Deviation (Percent)
E. Kentucky		
1-1/2" x 3/8"	0.75	0.69
3/8" x 14 Mesh	0.93	0.89
14 Mesh x 0	0.86	0.71
Maryland		
1-1/2" x 3/8"	0.55	0.50
3/8" x 14 Mesh	0.71	0.54
14 Mesh x 0	0.72	0.47
Ohio		
1-1/2" x 3/8"	0.57	0.44
3/8" x 14 Mesh	0.72	0.48
14 Mesh x 0	0.76	0.48
Pennsylvania		
1-1/2" x 3/8"	0.62	0.73
3/8" x 14 Mesh	0.85	0.86
14 Mesh x 0	0.81	0.74
Tennessee		
1-1/2" x 3/8"	0.10	0.09
3/8" x 14 Mesh	0.10	0.10
14 Mesh x 0	0.12	0.11
Virginia		
1-1/2" x 3/8"	0.31	0.24
3/8" x 14 Mesh	0.35	0.28
14 Mesh x 0	0.30	0.20
W. Virginia		
1-1/2" x 3/8"	0.58	0.60
3/8" x 14 Mesh	0.78	0.71
14 Mesh x 0	0.81	0.66

^aThe test of the Btu yield estimates was conducted *after* the washability data had been adjusted, for size and probable error, by the modified Skea and Rubin model. Thus, the bottom sizes presented in this table correspond to the adjusted, as opposed to original, data. The data adjustments made by the model are discussed later in this chapter.

that constitute the U.S. DRB, given information on the raw quality of the coal and the required clean coal quality. (The reader will recognize this objective as being similar to that of this study.) Two different approaches to this problem were considered. The first approach would have involved the development of a *single* engineering/economic model, for use as the AUSM cleaning component, that would have required as input a DRB characterized as to raw coal quality and washability. This approach presented a problem: although a large amount of data on the raw quality of the coals contained in the DRB is available, information on the *washability* of these coals is much more limited. The data limitations would obviously reduce the accuracy of the assignments of washability characteristics to the DRB coals.

The second approach (which was finally chosen by Skea and Rubin as the better of the two) represented an attempt to address this problem. Essentially, this approach involved an attempt to establish a correlation between raw coal quality and washability. Such a correlation, if it could be established, would enable the substitution of quality data for washability data as input to the model. The need for washability data, available only in limited quantities, would be obviated.

To determine whether the hoped-for correlation exists, Skea and Rubin first developed their engineering/economic model, which was used to process the data contained in the DOE washability data base. As originally developed, this model generates estimates of the optimum yield and preparation costs associated with washing a coal, of given raw quality and washability characteristics, to meet specified clean coal quality requirements. Separate estimates can be developed for each of the three different mechanical cleaning levels. For each level, the model was run for each sample contained in the DOE washability data base. The samples were washed in 5-percent sulfur reduction increments up to the maximum possible level of sulfur reduction (as determined by the pyritic sulfur content of the coal and the washing capabilities of each preparation level), yielding separate cost and yield estimates for each increment. The results were then pooled by region and preparation level and used as the data base for the regression analysis of the relationship between raw quality and washability.

For the regression analysis, the preparation plant yield, as predicted by the model, was used as the dependent variable; and the raw coal sulfur, ash, and Btu contents (from the washability data), along with the specified fractional reduction in sulfur, were used as the independent variables. The analysis indicated that the yield, predicted using the washability data and the engineering/economic model, was indeed significantly correlated with the raw quality characteristics of the washability samples. Thus, Skea and Rubin concluded that the regression equations could be used to predict the yield resulting from the preparation for any and all coals contained in the DRB, given data on the raw quality of the coals and the desired fractional sulfur reduction. In other words, the preparation plant yield could be predicted *without* washability data; in effect, the regression analysis indicated that a significant correlation exists between coal quality and washability, and therefore that the former could be substituted for the latter. On this basis, Skea and Rubin developed their regression model, which consists of the yield regression equations for each region and preparation plant level, along with other regression equations that relate yield to preparation plant costs.

- The sample sizes are artificially high because they are based on the output of the engineering/economic model rather than on the observed washability data.

- There exists a potentially serious problem of autocorrelation arising from the pooling of data for multiple sulfur reduction levels at each sample point.

Because of these problems (discussed in greater detail in Appendix A), the observed significance of the dependent variables may be illusory. In other words, the proposed correlation between raw quality and washability is not established by the regression analysis. Furthermore, it must be noted that the results generated by the regression model would be useful only for regional-level analyses of potential SO₂ reduction because the regression equations were developed at the regional level. The regression equations cannot account for the very real differences in washability that can exist between coals of similar quality from the same region.

For these reasons, it was decided to use the engineering/economic model, rather than the regression model, as the basis for this study. Using this model, the approach to the problem was essentially the same as the first approach considered, but eventually rejected, by Skea and Rubin. To reduce the impact of the problems caused by the size of the DOE washability data base, the data base was supplemented with information from several other sources, principally the Bureau of Mines. As a result, the washability data base used for this effort was approximately 50 percent larger than that used by Skea and Rubin. The degree to which this larger data base provides coverage of the DRB will be discussed later in this chapter.

Following is a general description of Skea and Rubin's engineering/economic model, and a discussion of the modifications made to the model. The model description will be brief; for additional detail, the reader is referred to Appendix C of the documentation of the Advanced Utility Simulation Model. The Skea and Rubin model performs three primary operations. First, it adjusts the laboratory washability data input by the user to reflect actual plant operating conditions. Two separate adjustments are made. First, the data are converted from "cumulative" to "non-cumulative" form. As was discussed in the preceding subsection, the data used as model input represent the results of washability tests performed on three separate size fractions of coal: 1-1/2 inch x 100 mesh, 3/8 inch x 100 mesh, and 14 mesh x 0. The results are thus cumulative with respect to size; i.e., the coarse-coal fraction *includes* mid- and fine-sized particles, and the mid-sized fraction includes fine coal. In the actual operating plants simulated by the model, on the other hand, the separate cleaning circuits handle *non-cumulative* size fractions; i.e., the coarse circuit handles only coarse coal (1-1/2 inch x 3/8 inch), the mid-sized circuit handles only mid-sized particles (3/8 inch x 14 mesh), and the fine coal circuit processes only the fines (14 mesh x 0). To simulate these separate circuits, washability data for particle size ranges corresponding to the ranges handled by the circuits are required; i.e., the cumulative washability data must be converted to non-cumulative form. The model performs the necessary adjustments.

The second washability data adjustment is made to account for the fact that the perfect (or nearly perfect) float-sink separations attainable in the laboratory cannot be duplicated by commercial

preparation plant equipment. In other words, in operating plants, unlike the laboratory, some particles with specific gravities less than the simulated specific gravity of separation sink, while some particles with specific gravities greater than the specific gravity of separation float. The degree of imperfection in the particle separation varies depending on the type of equipment used in each cleaning circuit and is measured by the "probable error" associated with the equipment.* The Skea and Rubin model uses equipment probable errors specified by the user to adjust the washability data to account for the imperfection associated with commercial cleaning equipment; assumptions regarding the equipment types used in each circuit, and the probable errors associated with these equipment types, are presented in Table 4.4. These assumptions conform to those used by Skea and Rubin, and appear to be reasonably representative of typical real-world practice.

After the two washability data adjustments, the model performs its second major task: using the adjusted washability data, along with information identifying (1) the preparation level that the model is to simulate and (2) the required clean coal sulfur content, the model determines the optimum yield for the given operating conditions. This determination is made using the Lagrange multiplier technique. Finally, using the calculated yield and other user-supplied assumptions, the model performs its third and final task: it estimates the capital and operating costs corresponding to the given conditions. The cost estimates are developed using equations that relate costs to the clean plant output (in tons/hour), weight yield, and other relevant operating and financial parameters. The estimates include only the costs of the cleaning process itself; neither the reductions in coal transportation and power plant operating costs resulting from cleaning, nor the value of the coal lost to the refuse, are included in the estimates. The economic assumptions used for all model runs are presented in Table 4.5. The estimates include only the costs of the cleaning

Table 4.4. Equipment and Probable Error Specifications for the Three Levels of Preparation

Level of Preparation	Topsizes	Midsizes	Finesizes
2	heavy medium cyclone (PE ^a = 0.03)	no cleaning	no cleaning
3	heavy medium vessel (PE = 0.03)	heavy medium cyclone (PE = 0.03)	no cleaning
4	heavy medium vessel (PE = 0.03)	heavy medium cyclone (PE = 0.03)	hydrocyclone (PE = 0.09)

^aPE = Probable Error.

* In actuality, the probable error associated with a given coal/refuse separation is dependent not only on equipment type, but also on the size range of the coal and the specific gravity of separation. Within the model, the particle size range handled by each piece of equipment is held constant (this reflects actual operation practice), and the simplifying assumption is made that probable error remains constant across all specific gravities of separations.

Table 4.5. Economic Assumptions for All Model Runs

Annual Plant Operation	3325 hours/year
Plant Output	500 dry tons/hour
Economic Life of Plant	20 years
Nominal Interest Rate	10 percent
Rate of Inflation	5 percent
Index Updating 1978 Base-Year Costs to Mid-1986 Dollars (Mid-1978 = 1)	1.484

process itself; neither the reductions in coal transportation and power plant operating costs resulting from cleaning, nor the value of the coal lost to the refuse, are included in the estimates.

To adapt the model to meet the objectives of this study, and to correct a number of problems discovered during the review of the model, modifications were made to Skea and Rubin's original version. These changes affected only the yield optimization and cost estimation routines (i.e., the second and third model functions); the washability data adjustment procedures were left unchanged. The following pages describe first the changes that were made to the model's cost estimating equations, and then the modifications to the yield optimization procedure.

Four basic modifications were made to the model's cost estimating procedure. The simplest of these was the deletion of thermal drying costs for level 4 preparation. Skea and Rubin assumed that thermal drying would be necessary at this level; however, a review of data on 109 operating plants indicated that, even for level 4 plants, thermal drying is the exception rather than the rule. Deletion of thermal drying costs from the model's capital cost equation was a very simple matter, since these costs were included as a separate term in the equation. The operating cost equation was not modified, since this equation did not reflect the costs associated with thermal drying.

The second modification was somewhat more complex. Both the capital and operating cost equations include factors that were derived from preparation cost estimates for 13 hypothetical prep plants designed to clean 11 coals. These coals were selected as being representative of the four major coal supply regions (Northern Appalachia, Central Appalachia, Midwest, and Central West), as representing significant quantities of reserves, and as covering a wide range of sulfur contents. The operating cost factors derived from the prep plant cost estimates are presented in Table 4.6; the procedure used to arrive at these factors was as follows. First, annual costs associated with a given cost component were summed together for each of the plants of a given preparation level. In the case of services costs, for example, this involved the summation of itemized power and water costs. The plant totals obtained were then converted to a cost per unit basis. For services costs, this involved the division of the plant cost totals by the raw coal tonnage processed annually by each plant. Finally, the unit basis costs were averaged across all plants of a given preparation level to yield the cost factors as presented in Table 4.6. The capital cost factors, which are presented in Table 4.7, were derived in a similar manner.

The methodology described above has problems. Although some of the 13 hypothetical plants use the same equipment types as those used both in this study and in Skea and Rubin's model

Table 4.6. Original Preparation Plant Operating Cost Factors^a

Variable Cost Element	Level of Preparation		
	2	3	4
Labor ^{b,c} (\$/hr)	135.24	139.35	224.90
Maintenance ^c (% of Total Capital Cost)	7.0	7.0	7.0
Services ^d (Cents/Metric Ton Raw Coal)	7.3	15.0	17.0
Chemicals ^{c,e} (Cents/Metric Ton Raw Coal)	2.8	4.7	7.8
Waste Disposal (\$/Metric Ton Rejected Coal)	1.10	1.10	1.10

^aAll costs shown are in 1978 dollars/cents. They are updated to 1986 in the model.

^bCost per hour of plant operation, based on two shifts, 250 days per year. An additional 30 percent of the labor costs is allowed as a payroll overhead.

^cAn additional 26 percent of these costs is allowed as a plant overhead.

^dWater and electricity costs per ton of raw coal feed.

^eCosts for magnetite, flocculent, methyl isobutyl carbinol (MIBC), and fuel oil per ton of raw coal.

Table 4.7. Original Preparation Plant Capital Cost Factors

Plant Section	Cost Factor (1978 Dollars) ^a
1. Storage and Handling	12,800
2. Cleaning	
Level 2	8,800
Level 3	15,300
Level 4	19,600
3. Thermal Drying	116,600
4. Clean Coal Handling	7,100
5. Refuse Handling	24,300

^aThese factors appear in equations that relate capital costs to the clean plant output (in tons per hour).

runs (see Table 4.4), others do not. Nevertheless, the cost factors were developed by averaging costs across all plants within a given preparation level. Thus, the cost factors correspond to average plant equipment configurations different from the configurations used to develop the model's yield estimates. As a result, costs estimated using the original Skea and Rubin cost equations represent the average costs of both low- and high-efficiency plants, while the model's estimated yields reflect only high efficiency (heavy media) plants; thus, costs may be understated relative to the estimated yields. As just one example of the biases that may be introduced into the estimated costs as a result of this problem, consider chemical costs (see Table 4.6). These costs consist largely of the costs of magnetite associated with dense medium equipment. When the chemical costs incurred by plants using methods other than dense medium methods are averaged together with the costs incurred by dense medium plants, it is clear that the resulting numbers will understate the true expenses incurred by plants employing dense medium processes. For example, the chemical costs factor estimated for level 2 plants is 2.8 cents per metric ton of raw coal (see Table 4.6). If only the costs for those plants employing dense medium cyclones had been used as the basis for determining the chemical costs factor, the result would have been 4.1 cents per metric ton of raw coal -- 48 percent higher than the actual estimated factor. Yet the yield estimated by the model will reflect the higher costs associated with magnetite replacement.

To correct this problem, new cost factors were derived by applying the methodology described above *only* to those hypothetical plants employing the same types of cleaning equipment as those that were used in model runs made for this study (see Table 4.4). The new operating cost factors are presented in Table 4.8. The reader will note that only the services and chemical cost factors changed; this is due to the fact that the other operating costs remained constant across all of the hypothetical plants within a given preparation level.

Table 4.9 presents the new capital cost factors. Because, for the 13 hypothetical plants, only the capital costs associated with cleaning (plant section number 2 in Tables 4.7 and 4.9) appear to depend on the level of preparation, it was assumed that only these costs vary depending on the types of cleaning equipment used. Therefore, the modification described above was applied only to the capital costs for cleaning. Nonetheless, a comparison of Tables 4.7 and 4.9 will indicate that modifications to the capital cost factors for other plant sections were made. Specifically, the factors for thermal drying and clean coal handling were dropped, the refuse disposal factor was changed, and a new factor for coal sampling was added. The clean coal handling factor was not actually deleted; rather, it was combined with the refuse handling factor. This change was needed when it was discovered that the costs used to derive the clean coal handling factor actually apply to refuse handling. The capital costs for the 13 plants exclude clean coal handling costs, which are assumed to be part of the mine costs rather than the preparation plant costs. Within the Skea and Rubin capital cost equation, the clean coal handling term was dropped. Finally, the new factor for coal sampling was added because the capital costs for sampling included in the costs for the 13 plants were not accounted for in any of the other cost factors. In the modified capital cost equation, the sampling factor appears as a constant (324,000 total dollars); i.e., it is assumed that this factor does not vary with preparation level, plant throughput, etc.

Finally, one new cost equation was added to the model's original equation. This equation calculates the capital costs associated exclusively with the cleaning equipment, using the term for the plant cleaning section (section 2 in Tables 4.7 and 4.9) from the model's total plant capital cost equation. The capital costs associated with the purchase and installation of the cleaning equipment are needed in addition to the total plant capital costs because, using these costs, one

Table 4.8. New Preparation Plant Operating Cost Factors^a

Variable Cost Element	Level of Preparation		
	2	3	4
Labor ^{b,c} (\$/hr)	135.24	139.35	224.90
Maintenance ^c (% of Total Capital Cost)	7.0	7.0	7.0
Services ^d (Cents/Metric Ton Raw Coal)	7.9	14.2	17.7
Chemicals ^{c,e} (Cents/Metric Ton Raw Coal)	4.1	5.7	7.2
Waste Disposal (\$/Metric Ton Rejected Coal)	1.10	1.10	1.10

^aAll costs shown are in 1978 dollars/cents. They are updated to 1986 in the model.

^bCost per hour of plant operation, based on two shifts, 250 days per year. An additional 30 percent of the labor costs is allowed as a payroll overhead.

^cAn additional 26 percent of these costs is allowed as a plant overhead.

^dWater and electricity costs per ton of raw coal feed.

^eCosts for magnetite, flocculent, methyl isobutyl carbinol (MIBC), and fuel oil per ton of raw coal.

Table 4.9. New Preparation Plant Capital Cost Factors

Plant Section	Cost Factor (1978 Dollars) ^a
1. Storage and Handling	12,800
2. Cleaning	
Level 2	8,800
Level 3	16,200
Level 4	19,400
3. Refuse Handling	31,400
4. Coal Sampling	324,000

^aThese factors appear in equations that relate capital costs to the clean plant output (in short tons per hour).

can estimate the costs of upgrading an existing plant from one preparation level to another by subtracting the cleaning equipment costs associated with the original plant from the cleaning equipment costs for the new plant. Thus, using the output from the modified model, both the costs for building new plants and the costs for upgrading existing plants can be estimated.

In addition to the above-described modifications to the model's economic equations, a modification was made to the model's yield optimization routine. As was discussed previously, the model uses the Lagrange multiplier technique to calculate the optimum yield given a required sulfur reduction level. For our purposes, we wanted an estimate of the optimum sulfur reduction given a specified Btu yield. That is, the Skea and Rubin procedure had to be reformulated to maximize coal quality (q) (i.e., maximizing sulfur reduction) for specific plant yields (y). For any particular washstream Skea and Rubin assumed that coal quality is described as a piecewise linear function of process yield. Conversely, the process yield for each washstream can also be described as a piecewise linear function of coal quality; that is, $y = y(q)$. Using Skea and Rubin's notation, it was assumed that there are N washstreams (each denoted by i) and specific gravity ranges (each denoted by r). Each specific gravity range represents washability data between contiguous specific gravity levels (each denoted by s). For example, the specific gravity range $r = 1$ corresponds to washability data delineated by the specific gravity levels $s = 1$ and $s = 2$. Thus, for each range category and washstream, the yield was expressed as:

$$Y_{i,r} = \rho_{i,r} + \mu_{i,r} Q_i \quad (1)$$

where Q_i represents the nonsulfur fraction; i.e., $Q_i = 1 - q_i$ and

$$\rho_{i,r} = \frac{Y_{i,s} Q_{i,s+1} - Y_{i,s+1} Q_{i,s}}{Q_{i,s+1} - Q_{i,s}} \quad (2)$$

$$\mu_{i,r} = \frac{Y_{i,s+1} - Y_{i,s}}{Q_{i,s+1} - Q_{i,s}} \quad (3)$$

the quality of the washed coal was expressed as:

$$\text{Quality} = \frac{\sum_i f_i Y_i Q_i}{\sum_i f_i Y_i} \quad (4)$$

where f_i is the weight or Btu fraction of washstream i .

The plant yield is

$$Y_p = \sum_i f_i Y_i \quad (5)$$

where Y_p is the target for the cleaning process. The coal quality can be rewritten as

$$\text{Quality} = \frac{1}{Y_p} \sum_i f_i Y_i Q_i = K_i f_i Y_i Q_i \quad (6)$$

where K is a constant. The optimization problem was thus reduced to maximizing the objective function $\sum_i f_i Y_i Q_i$ for nonsulfur content subject to the constraint on plant yield $\sum_i f_i Y_i - Y_p = 0$.

The optimization problem was solved by the Lagrange multiplier method. The Lagrangian function is

$$L(Q_i, \lambda_i) = \sum_i f_i Y_i Q_i - \lambda_i (\sum_i f_i Y_i - Y_p) \quad (7)$$

where λ_i is the Lagrange multiplier for washstream i .

Taking the partial derivatives of the Lagrangian function with respect to λ_i and Q_i gives

$$\frac{\partial L}{\partial \lambda_i} = \sum_i f_i Y_i - Y_p = 0 \quad (8)$$

$$\frac{\partial L}{\partial Q_i} = f_i Y_i + f_i Q_i \frac{\partial Y_i}{\partial Q_i} - \lambda_i f_i \frac{\partial Y_i}{\partial Q_i} = 0 \quad (9)$$

However, from equation (1)

$$\frac{\partial Y_i}{\partial Q_i} = \mu_i \quad (10)$$

Combining equations (9), (10), and (1) yields

$$\frac{\rho_i}{\rho_i} + 2Q_i - \lambda_i = 0 \quad (11)$$

Let

$$\sigma_i = \frac{\rho_i}{\mu_i} \quad (12)$$

Then

$$Q_i = \frac{1}{2} (\lambda_{i,r} - \sigma_i) \quad (13)$$

Substituting (13) into (1) gives for each range

$$\lambda_{i,r} = \frac{2}{\mu_{i,r}} Y_{i,r} - \sigma_{i,r} \quad (14)$$

Since $Y_{i,r}$ is discontinuous at each specific gravity level in the washability data, the Lagrange multiplier $\lambda_{i,r}$ is a single-valued function of Q_i between specific gravity levels and has multiple values at each specific gravity level. The fixed and variable Lagrange multiplier are as follows:

$$\lambda_{i,r}^f = \frac{2}{\mu_{i,r}} Y_{i,s} - \sigma_{i,r} \quad \text{fixed} \quad (15)$$

$$\lambda_{i,r}^v = \frac{2}{\mu_{i,r}} Y_{i,s+1} - \sigma_{i,r} \quad \text{variable} \quad (16)$$

During the optimization procedure some washstream characteristics are fixed while others vary. Consequently, the constraint equation (8) is separated into fixed and variable parts as follows:

$$\begin{array}{cc} \text{variable} & \text{fixed} \\ \sum_i f_i Y_i + & j f_j Y_j - Y_p = 0 \end{array} \quad (17)$$

where the variable washstream characteristics are summed over i and the fixed washstream characteristics are summed over j . Substituting (1) and (13) into the variable portion of (17) gives

$$\frac{1}{2} \sum_i f_i \rho_{i,r} + \frac{\lambda}{2} \sum_i f_i \mu_{i,r} + \sum_j f_j Y_j - Y_p = 0 \quad (18)$$

where λ is a global Lagrange multiplier chosen from the local $\lambda_{i,r}$'s with the highest value that meets all constraints.

Let

$$A = \frac{1}{2} \sum_i f_i \rho_{i,r} \quad (19)$$

$$B = \frac{1}{2} \sum_i f_i \mu_{i,r} \quad (20)$$

$$C = \sum_j f_j Y_j \quad (21)$$

Then Equation (18) may be rewritten as follows

$$\lambda = \frac{1}{B} [Y_p - (A + C)] \quad (22)$$

Optimum quality was determined by an algorithm that searches over segments of washability data for values of local $\lambda_{i,r}$'s that satisfy the constraint equation (5). Local $\lambda_{i,r}$'s for each washstream were compared to the global lagrange multiplier for all washstreams. An optimum solution occurs when the global Lagrange multiplier equals or exceeds the local $\lambda_{i,r}$ values.

Once the model modifications described above were completed, the model could be translated into a series of computer programs. Since the engineering/economic model used for our analyses is not a part of the AUSM, Skea and Rubin's original programs were unavailable; therefore, it was necessary to begin programming from scratch. The programs that make the necessary preliminary adjustments to the washability data were written in the SAS (Statistical Analysis System) language. The yield optimization and cost estimating routines were written in FORTRAN. Finally, the programs were run for the 18 different combinations of preparation level and Btu yield presented in Table 4.1. This completed the first step of the effort.

Step 2:

Distribution of the DRB by Coal Type

The objective of the second step was to characterize the U.S. DRB by coal type (see Figure 4.1). To accomplish this, the following principal data sources were employed:

- The 1983 U.S. Demonstrated Reserve Base (DRB)
- The 1971 bed-county level Demonstrated Reserve Base (DRB)
- The DOE washability data
- The EIA analytical file containing coal quality information

The 1983 DRB was used to establish the quantity of coal available for mining by state, mining method, and coal rank; the 1971 bed/county level DRB was used to distribute the 1980 state-level quantities to the bed/county combinations within each state; and the raw coal quality data contained in the EIA-7A Supplement data base, the DOE washability data base, and the EIA analytical file were used to assign the 1983 bed/county level reserve quantities to coal types.

The 1983 DRB presents estimates of the available quantity of coal by state, mining method, and coal rank. However, it does not provide any information on the quality of the available coal.

Thus, it was necessary to merge the DRB reserve estimates with coal quality data to derive the necessary coal type distribution.

How might the DRB estimates be merged with available quality data? The optimum procedure would be as follows. First, each coal sample for which a quality analysis is available would be located geologically and geographically; i.e., the coal seam and the location within the seam from which the sample was taken would be determined and plotted on a map of the seam. Then, for each seam, the "area of influence" of each sample point would be determined by drawing boundaries around each point, equidistant between the point and the other points that surround it. The area within the boundaries would represent the area of influence for the sample point. Next, the bed/county level 1971 DRB estimates would be summed to the bed/state level. Finally, these bed/state level DRB estimates would be subdivided into separate reserved blocks for each sample point on the basis of the area of influence corresponding to each point. That is, the area of influence for each point would be divided by the total area covered by the seam containing the point, and this fraction would then be multiplied by the total reserve estimate for the seam to yield the reserve block to be assigned to the sample point. Each separate reserve block would then be assigned the quality corresponding to the sample to which the block has been assigned; the resulting distribution of 1971 reserves by quality could then be applied to the 1983 state-level DRB estimates to yield a 1983 reserve distribution by coal quality.

As stated above, this would be the optimum procedure for merging the DRB estimates with the available quality data. Unfortunately, it is not a feasible procedure for two reasons. First, the data and information needed to carry it out are for the most part unavailable. Not all seams have been mapped, and although the coal samples for which quality analyses are available are identified, in existing data bases, as to the seam and county of their origin, their locations within the origin counties are not specified. Second, even if this information were available, the effort required to map the area of influence of each sample point for which quality data are available would exceed, by orders of magnitude, the resources available for this project. This is because there are roughly 33,000 raw quality observations available from the various sources.

Therefore, a key simplifying assumption was made. It was assumed that, for lack of better information, the areas of influence for all sample points within a given bed and county are equal. The adoption of this assumption obviated the need for mapping the points; instead, the 1971 bed/county reserve estimates could simply be distributed in equal shares to each point within a given bed/county combination.

Tables 4.10 and 4.11 present the definitions of the various coal types; as these tables indicate, the coal type assignments are based on the combination of the rank, the heat content, and the SO₂ content of the coal. Thus, as a first step in developing the coal type assignments, we assigned a coal rank to every bed/county, county/state, and bed/region combination for which rank data are available. Two primary sources were used to make the rank assignments. If the 1983 DRB

Table 4.10. Btu Content Categories

Btu Code	Million Joules/Kg ^a	Rank of Coal ^b
Z	Greater than 30.22	Bituminous
H	26.75-30.22	Bituminous
M	Less than 26.75	Bituminous
S	--	Subbituminous
L	--	Lignite

^aDry basis.

^bCoal rank is defined according to the American Society for Testing and Materials Standard Specification for Classification of Coals by Rank (ASTM Designation D 388-66).

indicated that all the coal within a given state is of one rank, then all the bed/county, county/state, and bed/region* combinations within the state were assigned the single DRB rank. If, on the other hand, the DRB indicated that the state contains coal of more than one rank, then the rank data included in the EIA-7A file were used to assign ranks to the various combinations. This file provides rank assignments for beds within individual mines; thus, by aggregating these rank data at the bed/county, county/state, and bed/region level, assignments could be made at each of these levels. In a few cases, the EIA-7A data indicated that a bed/county, county/state, or bed/region combination contained coal of more than one rank; these combinations were assigned a rank of "M" for multiple.** Also, EIA-7A rank data were not available for some bed/county, county/state, or bed/region combinations that contain reserves (according to the 1971 bed/county level DRB). These combinations were also assigned a rank of "M."

The method used to determine the actual ranks for combinations assigned a rank of "M" is described later.

After assignment of ranks (either bituminous, subbituminous, lignite, or "M") to the various bed/county, county/region, or bed/region combinations, all available quality data were assembled. As discussed above, these data were obtained from three different sources. The raw quality data in the EIA analytical file and DOE washability data base are on a dry basis and are identified as to the county and bed to which they correspond. The EIA-7A Supplement data base provides average mine-level quality data for the coal produced by each operation that mined over 90,700 metric tons (100,000 short tons) in 1983. In addition to providing the average Btu and sulfur content for each mine's 1983 production (on a dry basis), the EIA-7A Supplement data also

* The term "region," as used here and in the remainder of this chapter, refers to a set of predefined coal-producing regions. In the East, these regions correspond to states in all cases except West Virginia, which is broken down into a northern and southern region, and Kentucky, which is subdivided into an eastern and western region.

** In a few cases, it was apparent that the rank data for multiple rank combinations were in error. For example, sometimes the rank data indicated the existence of coal of a rank for which there are no reserves (according to the state/rank level 1983 DRB). These obvious errors were corrected.

Table 4.11. Sulfur Content Categories

Sulfur Code ^a	Nanograms SO ₂ per Joule ^b
A	0 - 257
B	258 - 343
C	344 - 516
D	517 - 645
F	646 - 860
G	861 - 1075
H	1076 - 1290
I	1291 - 1721
J	1722 - 2582
K	2583 - 3443
L	Greater than 3443

^aThe coal type is defined by the combination of the Btu code and sulfur code. For example, type HB coal is bituminous coal with a heat content between 26.75 and 30.22 million joules per kilogram and a sulfur content between 258 and 343 nanograms per joule. Likewise, type SA coal is subbituminous coal (of any Btu content) with a sulfur content between 0.00 and 0.40 pounds/million Btu.

^bSO₂ equivalent of the sulfur content (dry basis) of the coal, based on the assumption that all of the sulfur contained in the coal is converted to SO₂.

indicate the county and bed(s) in which each mine is operating and the mining method (surface or underground) employed by each operation.

Thus, there are two primary differences between the Supplement data and the data from the analytical file and washability data base:

- The Supplement data are identified as to mining method, whereas the analytical and washability data are not.
- In the case of multiple-seam mining operations, the analyses in the Supplement data base correspond to more than one seam; the analyses in the analytical file and washability data base each correspond to a single seam.

In the following paragraphs, each of these problems is considered in turn.

Because the 1971 and 1983 DRB estimates are broken down by method of mining (surface and underground), but only some of the available quality data (i.e., the Supplement data) are likewise identified as to mining method, it was necessary to handle each quality observation slightly differently depending on whether or not it was identified as corresponding to reserves of a particular mining method. Quality observations from the Supplement data base, which are identified as representing either surface or underground coal, were assigned to the bed/county/mining method combinations to which they correspond. Observations from the analytical file and washability data base, on the other hand, were assigned to both the surface and underground reserves for the bed/county combinations to which they correspond. If, for example,

one analytical file observation and one Supplement file observation corresponding to surface-minable coal were available for a given bed/county combination, then that combination's underground reserves would be assigned to the analytical observation, whereas its surface reserves would be split into two equal shares, one of which would be assigned to the Supplement observation.

Supplement observations representing more than one seam were handled in a manner similar to observations not identified as to mining method; i.e., such observations were assigned to each of the bed/county combinations to which they correspond. Suppose, for example, that one Supplement file observation corresponds to the surface reserves in seams A and B in a given county, and one other observation is available for the seam B surface reserves. In this case, all of seam A's surface reserves and half of seam B's surface reserves would be assigned to the Supplement observation. The remainder of seam B's surface reserves would be assigned to the other observation.

The washability data also differ from the data from the other two sources in two important respects. First, the washability data contain three separate raw coal analyses for each sample: one each corresponding to the 1-1/2 inch x 100 mesh, 3/8 inch x 100 mesh, and 14 mesh x O size fractions. Each of these separate size fractions was created by subdividing the original sample into standardized portions; thus, to obtain the overall raw quality of the sample, the weighted average raw quality for the three fractions was calculated. This weighted average was used to make the coal type assignments.

Second, whereas raw coal analyses are provided for each and every sample of coal included in the washability data base, the analytical data base contains samples of clean as well as raw coal, and much of the coal quality data from the Supplement file correspond to cleaned or partially cleaned coal. Therefore, clean coal analyses were screened from the analytical and supplement data before merging these data with the DRB.

Once the various data-related tasks described above were completed, and the analytical, washability, and Supplement data shaped into a usable form, the 1971 DRB reserves falling in each bed/county/mining method combination were subdivided into "x" equal shares, where x represents the number of quality observations falling in the same combination. Each of these reserve shares was assigned a coal type based on the Btu and sulfur content of the quality analysis corresponding to the share and the rank assigned to the bed/county combination to which the share belongs. For those shares corresponding to bed/county combinations assigned a rank of "M," the actual coal rank was determined using the Btu content of the analysis assigned to the share.

This completed the assignment of coal types to reserves at the bed/county level; however, the available quality data did not cover all bed/county combinations that contain 1971 bed/county reserves. Bed/county/mining method reserve blocks that could not be assigned a coal type at the bed/county/mining method level were instead assigned a coal type on the basis of all quality observations available for the county/mining method combination containing the reserve block (including observations used for assigning coal types at the bed/county/mining method level). The assignment of coal types at the county/mining method level was made following the same procedure used at the bed/county/mining method level: the unassigned reserves falling in each bed/county/mining method combination were first subdivided into equal shares corresponding to

each quality observation assigned to the combination, and then each share was assigned a coal type on the basis of the Btu and sulfur content for the corresponding observation and the rank for the corresponding county. Reserve shares falling in counties assigned a rank of "M" were assigned actual ranks on the basis of the Btu contents of the quality observations corresponding to the shares.

Even at the county/mining method level, the available quality data did not cover all the reserves. Reserves for those bed/county/mining method combinations that could not be assigned a coal type at the county/mining method level were instead distributed to coal types at the bed/region/mining method level. The same coal type assignment procedure that was applied to the bed/county/mining method and county/mining method reserves was applied at the bed/region/mining method level.

Table 4.12 provides a regional-level percentage breakdown of the 1971 reserves by the level at which they were assigned a coal type. It shows, for example, that 89.3 percent of Alabama's underground reserves was assigned a coal type at the bed/county level, that 10.6 percent was assigned a coal type at the county level, and that the remaining 0.1 percent was assigned a coal type at the bed/state level. As can be seen, some reserves assignments could not be made even at the bed/region/mining method level; however, with the exception of Alabama's surface reserves (a large portion of which lies in virgin lignite fields), the percentage of reserves left unassigned was small. Instead, the majority of the reserves, at least in the eastern regions, were assigned at the bed/county level. In fact, in no case was more than 40 percent of the reserves for the critical eastern regions left unassigned after the first bed/county step; the unassigned percentage ranged from a high of 36 percent for North West Virginia's surface reserves to a low of 6 percent for Ohio's surface coal.

The application of the coal type assignment methodology described above yielded a distribution of the 1971 DRB by coal type. Because the 1983 DRB differs from the 1971 DRB, it was necessary to apply the 1971 coal type distribution (for those reserves that were covered at the three levels of aggregation) to the 1983 DRB estimates to obtain a final coal type distribution as of 1983. The following equation was used to develop the 1983 distribution from the 1971 distribution:

$$\left(\frac{CT171_{i,j,k,m,n,p}}{T71_{i,j,m}} \right) (T83_{i,j,k,m}) = CT83_{i,j,k,m,n,p}$$

where

- | | | |
|------------------------------|---|---|
| CT171 _{i,j,k,m,n,p} | = | The 1971 reserves assigned to coal type m at either the bed/county/mining method, county/mining method, or bed/region/mining method level for region i, rank j (bituminous, subbituminous, or lignite), mining method k (underground or surface), county n, and bed P. |
| T71 _{i,j,k} | = | The total quantity of reserves (as of 1971) in region i of rank j (bituminous, subbituminous, or lignite), amenable to mining using method k (surface or underground), that was assigned at either the bed/county/mining method, county/mining method, or bed/region/mining method level. |

Table 4.12. Percent of Total Reserves Assigned a Coal Type at Each Level of Aggregation

Region	Underground Reserves				Surface Reserves			
	Bed/ County	Region/ County	Bed/ Region	Un- assigned	Bed/ County	Region/ County	Bed/ Region	Un- assigned
AK	0.0	99.6	0.4	0.0	0.0	11.8	88.2	0.0
AL	89.3	10.6	0.1	0.0	10.1	3.2	0.0	86.7
AR	95.3	0.0	4.7	0.0	79.0	11.6	9.4	0.0
AZ	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
CN ^a	43.8	46.0	9.8	0.3	4.7	95.3	0.0	0.0
CS ^b	25.0	68.4	6.5	0.2	0.0	100.0	0.0	0.0
EK ^c	71.4	28.4	0.3	0.0	66.1	33.4	0.5	0.0
EM ^d	0.0	0.0	0.0	0.0	0.0	35.8	64.2	0.0
IA	61.0	30.9	6.7	1.5	0.0	0.0	0.0	0.0
IL	72.6	16.9	9.4	1.1	81.8	10.3	7.9	0.0
IN	70.2	21.0	8.7	0.1	83.6	14.4	0.7	1.3
KS	0.0	0.0	0.0	0.0	82.2	15.7	0.3	1.8
MD	89.0	11.0	0.0	0.0	79.0	21.0	0.0	0.0
MO	51.7	30.9	17.4	0.0	62.4	12.5	24.3	0.9
ND	0.0	0.0	0.0	0.0	0.0	78.6	21.4	0.0
NM	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0
NV ^e	64.2	29.6	5.3	0.9	63.9	35.5	0.5	0.1
NW ^f	16.6	83.4	0.0	0.0	90.2	9.8	0.0	0.0
OH	89.3	10.7	0.0	0.0	94.0	5.9	0.1	0.0
OK	51.1	48.2	0.6	0.0	83.2	14.0	2.8	0.0
PA	90.3	9.6	0.1	0.0	91.4	8.5	0.1	0.0
SV ^g	79.9	15.0	5.0	0.1	78.8	16.0	4.8	0.4
SW ^h	11.3	88.7	0.0	0.0	16.3	83.7	0.0	0.0
TN	90.4	9.6	0.0	0.0	87.2	12.7	0.0	0.0
TX	0.0	0.0	0.0	0.0	0.0	37.0	63.0	0.0
UT	0.0	99.4	0.0	0.6	0.0	93.1	6.9	0.0
VA	77.8	22.2	0.0	0.0	87.2	12.8	0.0	0.0
WA	12.8	87.2	0.0	0.0	0.0	100.0	0.0	0.0
WK ⁱ	91.2	8.8	0.0	0.0	69.4	29.1	0.0	1.5
WM ^j	0.0	97.2	2.8	0.0	0.0	96.2	3.8	0.0

^aCN = northern Colorado

^bCS = southern Colorado

^cEK = eastern Kentucky

^dEM = eastern Montana

^eNV = northern West Virginia

^fNW = northern Wyoming

^gSV = southern West Virginia

^hSW = southern Wyoming

ⁱWK = western Kentucky

^jWM = western Montana

$T83_{i,j,k}$	=	The total quantity of reserves (as of 1983) in region i of rank j (bituminous, subbituminous, or L lignite), amenable to mining using method k (surface or underground).
$CT83_{i,j,k,m,n,p}$	=	The calculated quantity of 1983 reserves to be assigned to coal type m for region i, rank j (bituminous, subbituminous, or lignite), mining method k (underground or surface), county n, and bed p.

By applying this equation to all the region/rank/mining method reserve estimates included in the 1983 DRB, for all bed/county/mining method/coal type reserve blocks assigned some quantity of 1971 reserves, a distribution of the 1983 DRB, by coal type, was generated.

Step 3:

Merging the Results from Steps 1 and 2

The output from the second step consisted of the 1983 DRB broken down into separate bed/county/mining method/coal type reserve blocks. Although each block was characterized as to its raw coal quality, or coal type, the blocks were still not characterized as to their amenability to SO₂ reduction through coal preparation. To develop the required SO₂ reduction characterization, the output from the modified Skea and Rubin Model was merged with the distributed DRB. The procedure used to accomplish this merge was very similar to that used to distribute the DRB to coal type.

The reader will recall that, for each sample included in the washability data, the modified Skea and Rubin model generated a table of SO₂ reduction and preparation cost estimates for various combinations of preparation level and Btu yield; the general form of these tables was presented in Chapter 3, Table 3.3. Each table was identified as to the sample to which it corresponded and the state, county, and bed from which the sample was taken. In addition, the overall raw coal quality of the sample, calculated in the second step, was used to assign a coal type to each table. To accomplish the merge, each reserve block included in the DRB was assigned to one of the tables just as, previously, blocks of reserves had been assigned to individual coal quality analyses. The potential SO₂ reduction and preparation cost estimates included in each table then became the reduction and cost estimates for each reserve block to which the table had been assigned.

Again, assignments were made first at the bed/county, then at the county, and then at the bed/region level. However, in this step, a fourth assignment level was added: those reserves that could not be assigned to an SO₂ reduction table at the bed/region level were assigned at the region level. There was one other important difference between the second and third steps. As discussed in the preceding subsection, the optimum approach to distributing reserves to coal quality samples is to pinpoint the samples geographically, and then determine the area of influence corresponding to each sample point. This optimum approach is equally applicable to distributing reserves to washability, as opposed to quality, samples. However, as was the case for the coal quality samples, the washability samples are not pinpointed as to their geographic location; they are identified as to their bed and county of origin, but their location within each county is unknown. Nonetheless, in the case of the washability samples, additional information exists which can be used to "locate" the samples within their origin counties. As was explained in the preceding subsection, the raw coal type was determined for each sample obtained from the

DOE data base. Coal quality is roughly correlated with geographic location; i.e., coals with similar qualities, located in the same bed and county, are typically located closer together than coals with dissimilar qualities.* Thus, the raw quality calculated for each sample could be used as a rough indication of the location of the sample's origin within the bed and county (or, alternatively, within the county, bed and region, or region); i.e., as an indication of which of the reserve blocks constituting the bed/county reserves originally contained the sample coal.

To make use of the coal type information associated with each washability sample to locate the sample, the following approach was used. For each succeeding step, or level of assignment, in the distribution process (e.g., the bed/county step, county step, bed/region step, etc.), the coal types assigned to each reserve block falling within a given bed/county, or county, or bed/region, or region, were compared with the coal types corresponding to each sample falling within the same bed/county, county, etc. On the basis of this comparison, each reserve block was subdivided into "x" equal shares, where x equalled the number of samples with coal types matching those of the reserve block. Each of the shares was then assigned one of the x samples, and the table of SO₂ reduction and cost estimates corresponding to that sample. When x equalled zero, the reserve block was subdivided into "y" equal shares, where y equalled the number of samples with a Btu type matching that of the reserve block and a sulfur type within one sulfur category of that of the reserve block. Again each reserve share was assigned to one of the y samples. Finally, when both x and y equalled zero, the reserve block was subdivided into "z" equal shares, where z equalled the number of samples with a Btu type matching that of the reserve block and a sulfur type within one sulfur category of that of the reserve block.

If x, y, and z all equalled zero, then the reserve block was simply split equally to each sample falling in the same bed/county, county, bed/region, or region as the reserve block. Thus, it was decided that, if a sample could not be found that fell within two sulfur categories of the reserve block's coal type, the attempt to use coal quality as an indicator of location should be discontinued. Finally, if no samples fell in the same bed/county, county, etc., as the reserve block, then the reserve block was carried along, unassigned, to the next assignment level; for example, if the reserve block fell in a bed/county combination for which no washability samples were available, then the block was assigned to a sample or samples at the county (or bed/region, or region) level.

It should be noted that, since the washability data obtained from the USBM¹ did not include information on Btu content, these data could not be used in the same manner as the DOE washability samples. Because the coal types corresponding to the USBM samples could not be determined, they were excluded from our calculations of x, y, and z and were assigned to a given reserve block only if no DOE samples fell within two sulfur categories of the reserve block's sulfur type. Thus, the USBM data were used as a secondary, rather than primary, data source, in cases where DOE samples were lacking; this was an appropriate use of the USBM data given that

* The practice of assigning areas of influence to quality sample points is based on the implicit assumption that coal quality and coal location are correlated; specifically, on the assumption that the quality of coal contained in area surrounding a sampling point is similar to (and can therefore be assumed to be equal to) the quality of the sample.

the values for Btu yield calculated for use with the data were not as accurate as the observed Btu yield values provided by the DOE database.

Table 4.13 provides a regional-level percentage breakdown of the reserves by the level at which they were assigned a washability sample. A comparison of this table with Table 4.12 will indicate that the degree of reserve base coverage provided by the washability data base is considerably less than that provided by the quality data base. This, of course, was expected; the quality data base contains over 30,000 raw coal analyses, versus only 1000 washability samples contained in the washability data base. Although it is true that, in general, less than half of each region's reserves were assigned to washability samples at the bed/county level, there were some notable exceptions: over 80 percent of Pennsylvania's surface and underground reserves, over 60 percent of Ohio's underground reserves, and 70 percent of its surface reserves, and over 50 percent of Illinois's and Indiana's surface reserves were assigned at the bed/county level.

Furthermore, even in those cases where the percentage of reserves covered at the bed/county level was lower than 50 percent, a significant portion of the total reserves was nonetheless assigned at this level, at least for the critical eastern regions: in the East, the bed/county coverages range from approximately 20 percent up to 50 percent.

For most of the eastern regions, the majority of the reserves not covered at the bed/county level were covered at the county level. Typically, 80 percent or more of the eastern regional DRBs were assigned by the time the county-level assignments were completed; the exceptions included Alabama's surface reserves, Illinois's surface and underground reserves, Indiana's underground reserves, northern West Virginia's surface reserves, western Kentucky's underground reserves, and Virginia's surface and underground reserves. Most of the remaining unassigned coal in these regions were covered at the bed/region level; regional-level assignments covered approximately 10 percent or less of the coal in all the eastern regions except Alabama (which contains a large quantity of undeveloped lignite) and Virginia.

Of course, it is clear that the reserve coverage provided by available washability data could be considerably better. Ideally, the percentages presented in Table 4.13 would closely approximate their counterparts in Table 4.12. That they do not makes manifest the key problem affecting this study and all other attempts to estimate the potential for reducing SO₂ through physical coal cleaning: the general lack of washability data. This problem is discussed more fully in Chapter 1 and Appendix B.

Step 4:

Aggregation of Results

The output from step 3 consisted of a reserve base subdivided into numerous small blocks, each assigned a coal type and a washability sample. Each washability sample in turn corresponds to a table of SO₂ reduction and prep cost estimates covering a range of possible preparation level and Btu yield combinations. Thus, simply by tracing each reserve block, through its assigned washability sample, to its corresponding SO₂ reduction and preparation cost table, it was possible to obtain estimates (directly from the table) of the SO₂ reduction that could be obtained, and costs that would be incurred, as a result of cleaning the coal contained in there serve block under various preparation options. However, the step 3 output was too disaggregated to allow easy analysis: it consisted of over 1000 SO₂ reduction/cost tables, and tens of thousands of reserve

Table 4.13. Percent of Total Reserves Assigned a Washability Sample at Each Level of Aggregation

Region	Underground Reserves				Surface Reserves			
	Bed/ County	Region/ County	Bed/ Region	Un- assigned	Bed/ County	Region/ County	Bed/ Region	Un- assigned
AK	0.0	21.0	79.0	0.0	0.0	2.1	97.4	0.0
AL	40.1	45.3	1.7	12.9	22.5	48.8	1.3	27.4
AR	16.2	69.1	14.6	0.0	25.1	52.9	18.5	3.5
AZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CN ^a	15.2	8.8	0.4	75.7	0.0	0.0	0.0	0.0
CS ^b	7.6	72.5	9.2	10.7	0.0	100.0	0.0	0.0
EK ^c	22.0	63.4	11.8	2.8	18.0	59.8	16.7	5.4
EM ^d	0.0	0.0	0.0	0.0	0.0	23.5	0.0	76.5
IA	33.7	20.0	25.3	21.0	0.0	0.0	0.0	0.0
IL	35.7	11.2	45.2	8.1	54.4	11.0	28.8	5.9
IN	38.2	30.4	29.8	1.6	57.3	23.5	9.4	9.8
KS	0.0	0.0	0.0	0.0	29.2	29.2	0.0	41.7
MD	82.7	17.3	0.0	0.0	65.9	34.1	0.0	0.0
MO	18.0	10.0	42.3	29.7	34.7	15.6	34.6	15.1
ND	0.0	0.0	0.0	0.0	0.0	36.2	63.8	0.0
NM	0.0	77.1	22.9	0.0	0.0	100.0	0.0	0.0
NV ^e	49.0	32.9	11.7	6.4	34.5	37.1	19.6	8.8
NW ^f	10.8	89.2	0.0	0.0	1.4	98.6	0.0	0.0
OH	64.6	34.2	6.2	0.0	74.4	25.1	0.5	0.0
OK	22.8	24.8	41.9	10.4	51.9	19.4	17.0	11.7
PA	84.8	12.1	3.0	0.0	82.5	10.8	6.2	0.5
SV ^g	25.3	55.2	13.7	5.8	26.8	53.8	12.5	6.9
SW ^h	1.9	73.7	8.4	16.0	2.5	55.1	15.4	26.5
TN	37.4	53.3	6.4	2.9	46.2	46.7	4.8	2.2
TX	0.0	0.0	0.0	0.0	0.0	21.0	79.0	0.0
UT	0.0	26.2	0.2	73.6	0.0	7.6	92.4	0.0
VA	25.1	32.6	18.6	23.7	24.3	21.2	26.2	28.3
WA	2.7	15.9	20.9	60.5	0.0	25.6	0.0	74.4
WK ⁱ	45.7	12.1	38.8	3.4	46.5	31.7	17.8	4.0
WM ^j	0.0	95.8	4.2	0.0	0.0	91.9	8.1	0.0

^aCN = northern Colorado

^bCS = southern Colorado

^cEK = eastern Kentucky

^dEM = eastern Montana

^eNV = northern West Virginia

^fNW = northern Wyoming

^gSV = southern West Virginia

^hSW = southern Wyoming

ⁱWK = western Kentucky

^jWM = western Montana

blocks -- one each for every region/county/bed/coal type/washability sample combination. Clearly it was necessary to aggregate this highly disaggregated raw data base into a more useable form. This aggregation of the step 3 output, which yielded the results presented in the next section, was carried out in two separate steps. First, the step 3 output data base was aggregated to the bed/county level, using the following equations:

$$FS_{g,h,i,j} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Bt_{g,h,k,m}) (S_{g,h,k,m}) (FS_{i,j,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Bt_{g,h,k,m}) (S_{g,h,k,m})}$$

$$CN_{g,h,i,j} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m}) (CN_{i,j,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m})}$$

$$CU_{g,h,i,j} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m}) (CU_{i,j,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m})}$$

$$OC_{g,h,i,j} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m}) (OC_{i,j,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m})}$$

$$Y_{g,h,i,j} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Y_{i,j,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m})}$$

$$Bt_{g,h} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Bt_{g,h,k,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m})}$$

$$S_{g,h} = \frac{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Bt_{g,h,k,m}) (S_{g,h,k,m})}{\sum_1^n (SR_{g,h,k,m} + VR_{g,h,k,m}) (Bt_{g,h,k,m})}$$

where

$SR_{g,h,k,m}$	=	quality of surface coal (in tons) contained in reserve block located in county g, bed h, with coal type k, assigned to washability sample m.
$VR_{g,h,k,m}$	=	quality of underground coal (in tons) contained in reserve block located in county g, bed h, with coal type k, assigned to washability sample m.
$Bt_{g,h,k,m}$	=	raw heat content of coal contained in reserve block located in county g, bed h, with coal type k, assigned to washability sample m.
$S_{g,h,k,m}$	=	raw SO ₂ content of coal contained in reserve block located in county g, bed h, with coal type k, assigned to washability sample m.
$FS_{i,j,m}$	=	estimated quantity of SO ₂ that would remain (as a fraction of the SO ₂ in the raw coal) after cleaning at preparation level i, heat content yield j, for washability sample m.
$FS_{g,h,i,j}$	=	estimated quantity of SO ₂ that would remain (as a fraction of the SO ₂ in the raw coal) after cleaning at preparation level i, heat content yield j, for all of the coal contained in county g, bed h.
$Y_{i,j,m}$	=	estimated weight yield (as a fraction) after cleaning at preparation level i, heat content yield j, for washability sample m.
$CN_{i,j,m}$	=	estimated capital costs (in dollars per clean ton) for a new preparation plant operating at preparation level i, heat content yield j, for washability sample m.
$CN_{g,h,i,j}$	=	estimated capital costs (in dollars per clean ton) for a new preparation plant operating at preparation level i, heat content yield j, cleaning coal from county g, bed h.
$U_{i,j,m}$	=	estimated capital costs (in dollars per clean ton) for purchasing and installing cleaning equipment for a preparation plant operating at preparation level i, heat content yield j, for washability sample m.
$CU_{g,h,i,j}$	=	estimated capital costs (in dollars per clean ton) for purchasing and installing cleaning equipment for a preparation plant operating at preparation level i, heat content yield j, cleaning coal from county g, bed h.
$OC_{i,j,m}$	=	estimated operating costs (in dollars per clean ton) for operating a preparation plant at preparation level i, heat content yield j for washability sample m.
$OC_{g,h,i,j}$	=	estimated operating costs (in dollars per clean ton) for operating a preparation plant at preparation level i, heat content yield j, cleaning coal from county g, bed h.
$Y_{g,h,i,j}$	=	estimated weight yield (as a fraction) after cleaning coal from county g, bed h, at preparation level i, heat content yield j.
$Bt_{g,h}$	=	average raw heat content for coal contained in county g, bed h.
$xS_{g,h}$	=	average raw sulfur content for coal contained in county g, bed h.
n	=	number of separate reserve blocks contained in county g, bed h.

The values of $Bt_{g,h,k,m}$ and $S_{g,h,k,m}$ were, in general, taken as the midpoints of the heat and SO₂ content ranges defining the coal type to which the reserve block was assigned.

Values for $FS_{g,h,j}$, $CN_{h,j}$, $CU_{g,h,j}$, and $Y_{g,h,j}$ were calculated for each of the 18 different combinations of preparation level and heat content yield simulated using the modified Skea and Rubin model; thus, for each bed/county combination a table of SO_2 reduction and preparation cost estimates, of the same form as that illustrated by Table 4.1, was obtained. In addition, average heat and sulfur contents for the coal contained in each bed/county combination were determined. Using these bed/county level estimates, we developed, at the state level, two separate tables containing SO_2 reduction and preparation cost estimates for the 18 preparation options -- one each for coal cleaned in 1983, and for coal not cleaned in 1983. This was accomplished by substituting, in the preceding equations, the bed/ county level reduction, cost, yield, and quality estimates for the original reserve block level estimates, and the 1983 clean and raw bed/county level production estimates (for mines that produced over 100,000 tons in 1983) for the reserve block tonnage estimates ($SR_{g,h,k,m}$ and $UR_{g,h,k,m}$). The summations were performed across all bed/ county combinations (within each region) that produced any raw or clean coal in 1983. Thus, as our final results, we obtained, for 1983's cleaned and uncleaned production, regional level estimates of SO_2 reduction and preparation costs for the 18 different preparation options were obtained. The cost estimates were converted from dollars per ton of coal cleaned to dollars per ton of SO_2 removed using the following equation:

$$C_{s,i,j,k} = \frac{(C_{c,i,j,k}) (Y_{i,j,k}) (2200)}{(S_i) (Btu_i) (1 - FS_{i,j,k})}$$

where

$C_{s,i,j,k}$	=	estimated cost (operating, plant capital, or cleaning equipment capital) in dollars per ton of SO_2 removed for state i, preparation level j, and heat content yield k
$C_{c,i,j,k}$	=	estimated cost (operating, plant capital, or cleaning equipment capital) in dollars per ton of clean coal for state i, preparation level j, and heat content yield k
$Y_{i,j,k}$	=	estimated fractional weight yield for state i, preparation level j, and heat content yield k
$FS_{i,j,k}$	=	estimated quantity of so remaining in state i's coal, as a fraction of SO_2 in the raw coal, after cleaning at preparation level j, heat content yield k
S_i	=	average raw SO_2 content for state i
Btu_i	=	average raw heat content for state i

The values of $C_{s,i,j,k}$ and $(1-FS_{i,j,k})$ were plotted against the heat content yield for each preparation level within each of the major coal producing states in the east. The plots are presented and discussed in the next section.

Results

As discussed in the preceding section, the final results of the potential SO₂ reduction analysis consisted of two separate sets of potential reduction and preparation cost estimates: one for that portion of the total 1983 production that was mechanically cleaned, and one for that portion that was not cleaned. Next, the results for the uncleaned production are presented; these results are followed by the clean production estimates. Both sets of estimates were developed, and are presented, at the state level; only the results for the major coal-producing states lying east of the Mississippi are included in the following presentation.

Uncleaned 1983 Production

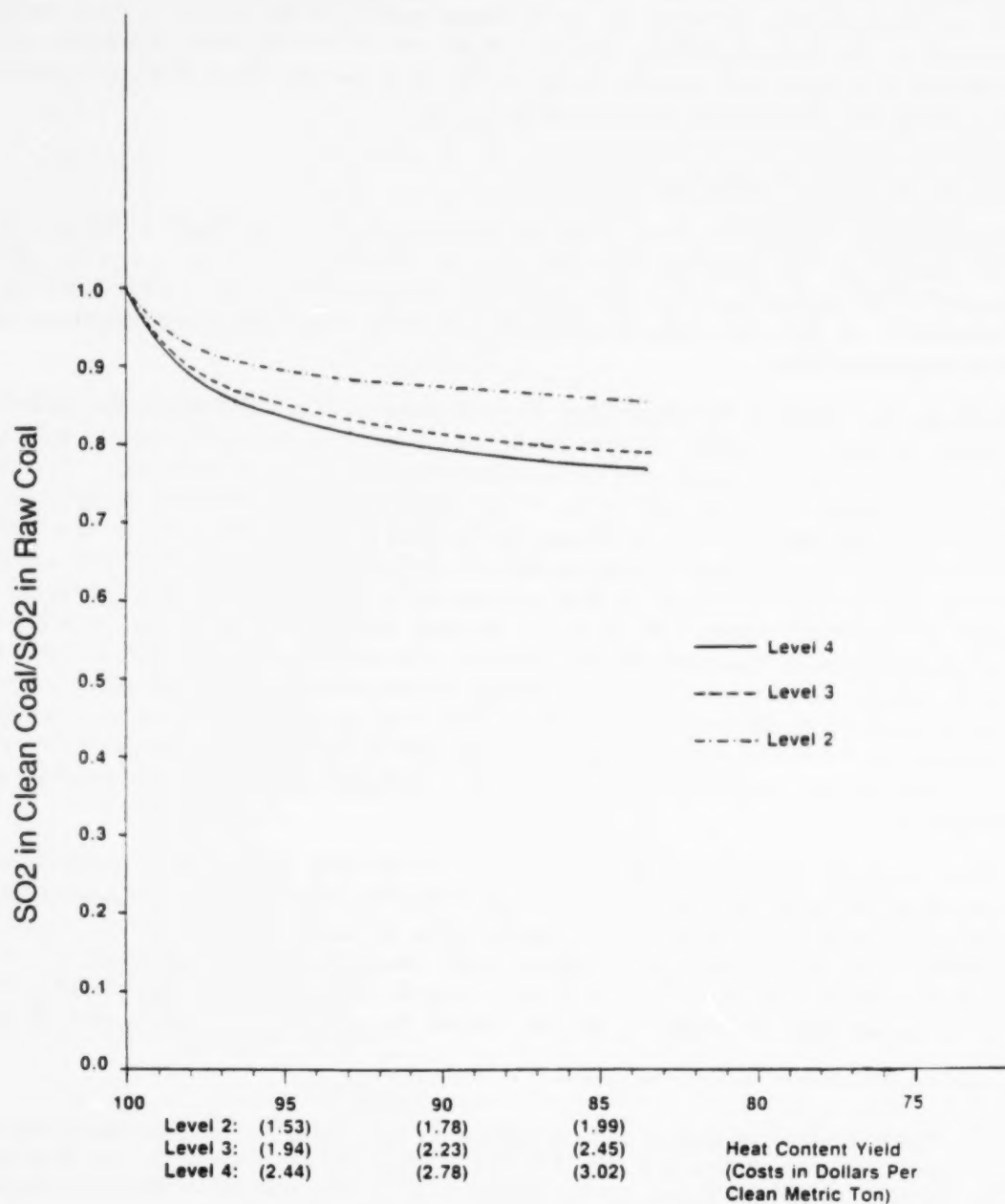
West Virginia. Figure 4.2 is a plot of the SO₂ reduction estimates for West Virginia's uncleaned 1983 production. The horizontal axis represents Btu yield; the vertical axis shows the estimated quantity of SO₂ remaining in the clean product (in nanograms per joule) as a fraction of the SO₂ contained in the raw coal (again in nanograms per joule). Three curves are presented; one for each preparation level.

As Figure 4.2 indicates, the largest drop in the quantity of SO₂ remaining in the cleaned coal occurs for Btu yields above 95 percent. Below 95 percent the curves are either linear or approximately linear (although they continue to follow a slight downward trend, indicating that continued reductions in the SO₂ content of the clean coal can be obtained through continued reductions in the Btu yield). If the 83-percent Btu yield point is taken as an economic cutoff, it will be found that, for level 3 cleaning, fully 71 percent of the total, economically attainable reduction in the SO₂ content of the clean product can be achieved by washing the coal at a Btu yield of 95 percent. Another 20 percent of the total attainable reduction can be achieved by reducing the yield to 90 percent, leaving 9 percent of the total achievable by further reductions in the Btu yield to 85 percent. For level 2 cleaning, 75 percent of the total attainable SO₂ reduction can be achieved by cleaning at a 95-percent yield, with an additional 15 percent attainable by reducing the yield to 90 percent. Thus, it appears that the benefits attainable by washing West Virginia's raw coal could, in large part, be achieved through a relatively "light" cleaning at high Btu yields.

What, precisely, are these benefits? Figure 4.2 shows that, for a level 2 preparation plant operating at a 95-percent yield, the SO₂ content of the coal could be reduced to approximately 89 percent of the raw SO₂ level.* At 90 percent yield the clean coal SO₂ content would be 87 percent of the raw content. Fairly significant improvements in these results could be attained by cleaning at level 3 as opposed to level 2; this change in levels drops the clean coal SO₂ contents to 85 percent and 81 percent of the raw content for yields of 95 percent and 90 percent,

* That is, if the nanograms of SO₂ per joule in the raw coal is "x," then the nanograms of SO₂ per joule in the clean coal is .89x. The total quantity of SO₂ in the clean coal, as percentage of the total in the raw coal, can be determined by multiplying .89 by the heat content yield of 95 percent. Thus, 84.5 percent of the SO₂ in the raw coal remains in the clean coal; i.e., if the tons of SO₂ in the raw coal is "x," then the tons of SO₂ in the clean coal is .845x.

Figure 4.2. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for West Virginia's 1983 Uncleaned Production



respectively. However, cleaning at level 4 would yield little additional benefit over level 3 cleaning; this reflects the fact that the quantity of fines in the raw coal (cleaned at level 4 but not at level 3) typically constitutes a relatively small percentage of the raw input to a cleaning plant.

Figure 4.2 provides information on the costs, as well as the SO₂ reduction, associated with cleaning West Virginia's uncleaned production. The sum of the estimated operating and annualized capital costs, in dollars per clean metric ton, is presented for the 95, 90, and 85-percent Btu yield points below these points on the horizontal axis. Separate estimates are presented, in parenthesis, for each of the three cleaning levels. Thus, for a Btu yield of 95 percent, level 2 cleaning costs are estimated at \$1.53/metric tons (1.39/short ton), level 3 costs are estimated to be \$1.94/metric ton (1.76/short ton), and level 4 costs are estimated to be \$2.44/metric ton (2.21/short ton). Reviewing the cost estimates, it can be seen that there are fairly substantial cost differences between the three levels. This fact, combined with the previous observation that little advantage, in terms of SO₂ reduction, can be gained by cleaning at level 4 as opposed to level 3, suggests that, in general, cleaning West Virginia's raw production at level 4 would probably not be worthwhile (assuming, of course, that SO₂ reduction is the sole objective). However, the benefits to be derived from cleaning at level 3, as opposed to level 2, may outweigh the disadvantages.

On the basis of the preceding analysis, two preparation options -- "light" cleaning and "heavy" cleaning -- were selected as being representative of the range of options illustrated by Figure 4.2. For light cleaning, level 3 preparation at a Btu yield of 95 percent was selected; heavy cleaning was set at level 3 and a 90-percent Btu yield. Table 4.14 presents the SO₂ reduction and cost estimates corresponding to these three cleaning options, on bases different from those used in Figure 4.2. As the table indicates, West Virginia produced 24,900,000 metric tons (27,400,000 short tons) of uncleaned coal in 1983; this represents 20.5 percent of West Virginia's total raw production for the year (see Chapter 2, Table 2.1). A total of 226,000 metric tons (249,000 short tons) of SO₂ could have been removed from this coal had it received a light cleaning; this corresponds to 19 percent of the total quantity of SO₂ in the raw coal. Heavy cleaning would have removed 322,000 metric tons (355,000 short tons) of SO₂ (or 27 percent of the raw SO₂ content) from the coal. A comparison of these reduction estimates with the current SO₂ reduction estimate for West Virginia (see Chapter 3, Table 3.3) will indicate that light cleaning of the uncleaned coal would have increased the actual SO₂ reduction achieved by the state (943,000 metric tons (1,039,000 short tons)) by 24 percent. This would have increased the state's actual reduction by 34 percent.

Interestingly, Table 4.14 shows that the costs of preparing the uncleaned coal, when measured in dollars per metric ton of SO₂ removed (as opposed to dollars per ton of coal produced), would be *lower* for heavy cleaning than for light cleaning. This is because the increase in costs from light to heavy cleaning, on a dollar per ton of clean coal basis, is more than offset by the corresponding increase in the quantity of SO₂ removed. As will be seen in the pages that follow, this is a very common phenomenon. It must, of course, be kept in mind that the reduction in capital and operating costs associated with increased intensity of cleaning is offset by the higher Btu loss resulting from lower yields. However, it is very important to note that costs, on a dollars per ton of SO₂ removed basis, decrease not only as the yield is decreased, but also as the preparation level is increased from 2 to 3. That is, for the same Btu yield, the costs associated with level 3 cleaning, when measured on a dollars per ton of SO₂ removed basis, are *lower* than the level 2 costs. It was for this reason that light cleaning was set at level 3 rather than level 2. Nonetheless,

**Table 4.14. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
West Virginia's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	3	3
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	24,900	24,900
Total SO ₂ Reduction (Thousand Metric Tons/Year)	226	322
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.19	0.27
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	198.14	151.58

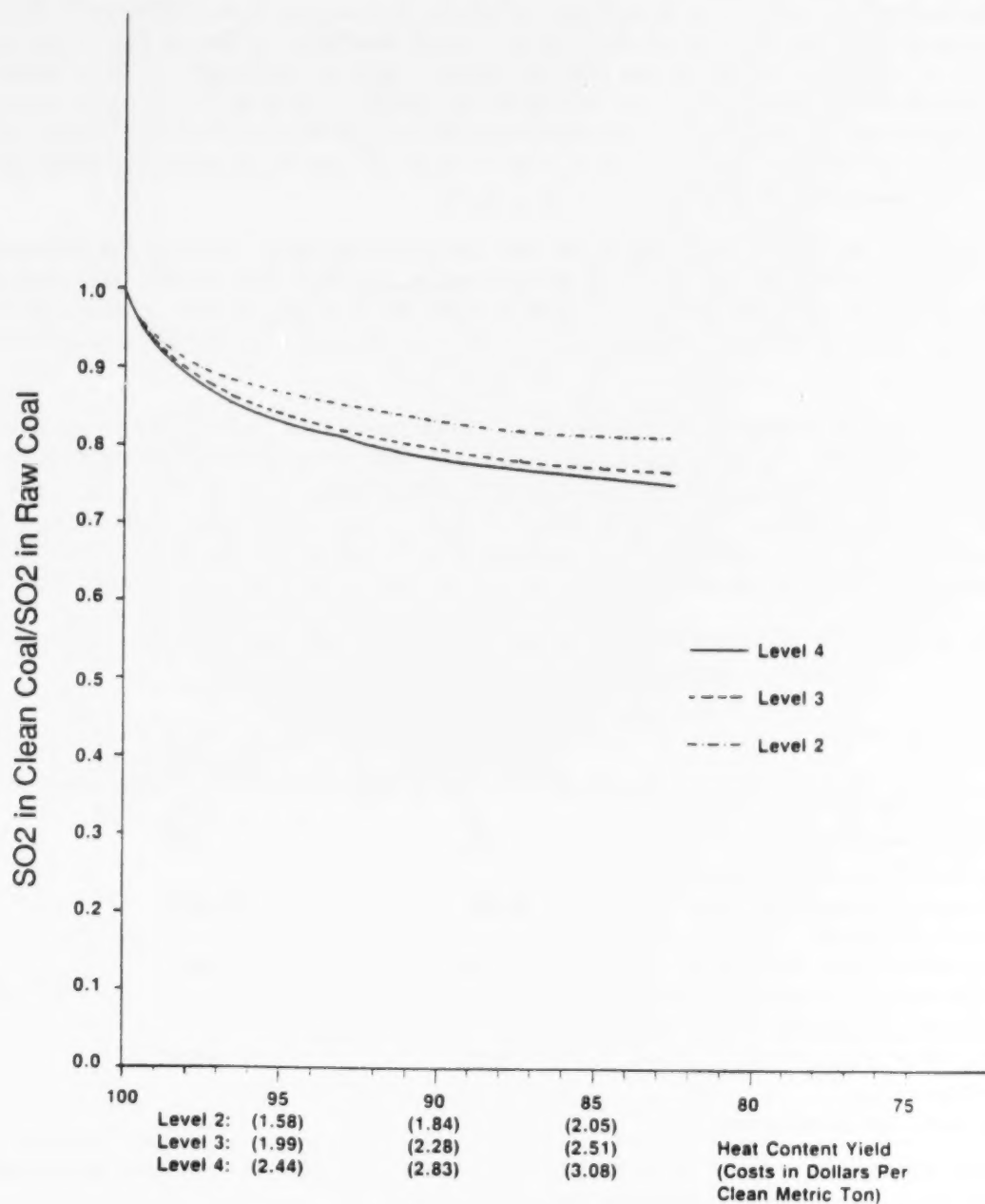
^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

in many "real world" situations it may be the dollars per ton of coal cleaned cost, rather than the dollars per ton of SO₂ removed cost, that is determining the choice of the preparation level.

Eastern Kentucky. Figure 4.3 presents the SO₂ reduction and preparation cost results for eastern Kentucky's 1983 unwashed production. A comparison of this figure with Figure 4.2 will indicate that eastern Kentucky's unwashed production is slightly more amenable to SO₂ reduction through mechanical cleaning than is West Virginia's unwashed coal. Washing the eastern Kentucky coal at level 3, to a Btu yield of 95 percent, would produce a clean product with an SO₂ content equal to 84 percent of that of the raw coal; additional cleaning to 90-percent and 85-percent yields would further reduce the clean coal SO₂ content to 80 percent and 77 percent of the raw SO₂ content, respectively. For level 2 preparation, the clean coal SO₂ content would be 87, 83 and 81 percent of the raw coal SO₂ content, at the 95, 90 and 85-percent yield levels, respectively. For eastern Kentucky, the largest drop in the clean SO₂ content below the 95-percent point constitutes a larger percentage of the total possible SO₂ reduction (using the 85-percent yield as the cutoff) than is the case for West Virginia. For level 3, 70 percent of the total possible reduction can be achieved at the 95-percent yield point, with an additional 17 percent attainable by reducing the yield to 90 percent. For level 2, the corresponding percentages are 68 and 21, respectively. Thus, further washing below the 90-percent point would prove somewhat more beneficial in eastern Kentucky than in West Virginia; however, for both states, the benefits to be derived from washing at low yields are somewhat marginal. Since we are dealing here with coal not being subjected to *any* cleaning, it seems reasonable to remain somewhat conservative in the selection of representative cleaning options. Therefore, for eastern Kentucky, heavy cleaning will be set at 90 percent, and light cleaning at 95 percent. It is important to keep in mind that these preparation option selections, like those for West Virginia,

Figure 4.3. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Eastern Kentucky's 1983 Uncleaned Production



are somewhat conservative, and that the SO₂ reduction estimates corresponding to heavy cleaning are *not* the maximums technologically attainable through physical coal cleaning.

Comparing Figures 4.2 and 4.3 shows that eastern Kentucky's uncleaned coal is not as responsive to changes in the preparation level as is West Virginia's unwashed production. Since the cost differentials between the levels, on a dollars per ton of coal cleaned, are as substantial for eastern Kentucky as for West Virginia, it would appear that the benefits to be derived from washing at level 4, as opposed to level 3, are relatively small. However, although the SO₂ reduction differentials between levels 2 and 3 are smaller for eastern Kentucky than West Virginia, they are not insignificant. Therefore, level 3 was once again selected as the heavy cleaning option. Light cleaning was set at level 2 because level 2 costs for eastern Kentucky are lower than level 3 costs even when measured in dollars per ton of SO₂ removed.

The specifications for the two cleaning options, along with the SO₂ reduction and preparation cost estimates associated with these options, are presented in Table 4.15. As the table indicates, eastern Kentucky produced 21,600,000 metric tons (23,800,000 short tons) of uncleaned coal in 1983; this represented a substantial portion (42.6 percent) of the state's total 1983 production (see Chapter 2).

Had this coal been subjected to a light cleaning, 132,000 metric tons (145,000 short tons) of SO₂, or 17 percent of the raw SO₂ content, could have been removed; a heavier cleaning would have increased the SO₂ reduction to 218,000 metric tons (240,000 short tons) metric tons, 28 percent of the raw SO₂ content). Referring to Table 3.3 in the preceding chapter, it can be seen that eastern Kentucky's preparation plant operators removed a total of 185,000 metric tons (204,000 short tons) of SO₂ from that portion of the area's 1983 production that was cleaned. Thus, it is

**Table 4.15. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Eastern Kentucky's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	2
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	21,600	21,600
Total SO ₂ Reduction (Thousand Metric Tons/Year)	132	218
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.17	0.28
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	236.05	191.57

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

apparent that substantial increases in the quantity of SO₂ removed from eastern Kentucky coal could be attained by washing the region's uncleaned production. Using light cleaning, the region's SO₂ reduction could be increased by 71 percent; heavy cleaning would yield a 118-percent increase. However, the costs associated with these gains, when measured in dollars per ton of SO₂ removed, are somewhat higher than the corresponding cost for West Virginia (\$236.05/metric tons (214.14/short ton) SO₂ versus \$198.14/metric ton (179.75/short ton) SO₂ for light cleaning, and \$191.57/metric tons (173.79/short ton) SO₂ versus \$151.58/metric ton (137.51/short ton) SO₂ for heavy cleaning). Once again, costs, in dollars per ton of SO₂ removed, decrease as intensity increases.

Virginia. Figure 4.4, which presents the SO₂ reduction and preparation cost results for Virginia's unwashed production, contrasts sharply with Figures 4.2 and 4.3. For instance, it shows that, below a relatively high Btu yield (approximately 93 percent for level 4 and 96 percent for level 2) further reductions in the SO₂ content of the clean coal are not possible. In fact, for level 4 the SO₂ content of the cleaned product, on a tons per million Btu basis, actually increases slightly below the 93-percent yield point, indicating that, as the yield is decreased beyond this point, the Btu loss begins to exceed the SO₂ reduction. Furthermore, the curves reach their minimum points at relatively high clean coal SO₂ contents; e.g., 92 percent (of the raw SO₂ content) for level 2 and 87 percent for level 4.

Two conclusions can be drawn from Figure 4.4: the benefits that could be derived by washing Virginia's uncleaned production are relatively small, and the benefits that could be obtained by washing this coal at low yields are nil. Furthermore, it is apparent that the differences between the curves for the three preparation levels are relatively small. Nonetheless, since the differences between the level 2 and level 3 curves are not negligible, and since the preparation costs, even when measured by a dollars per ton of SO₂ removed, are higher for level 3 than for level 2, it was decided that different levels should be selected for the two representative cleaning options. Light cleaning was therefore defined as level 2 preparation at a 97-percent Btu yield, while level 3 preparation at a 96-percent yield was selected as the heavy cleaning options.

Table 4.16 presents the results for light and heavy cleaning. As can be seen, the quantities of SO₂ that could have been removed from the 5,800,000 metric tons (6,400,000 short tons) of uncleaned Virginia production are very small—only 16,000 metric tons (17,600 short tons), 11 percent of the raw SO₂ content, using light cleaning and 21,000 metric tons (23,100 short tons) using heavy cleaning. These tonnages represent 36 percent and 47 percent of the total quantity of SO₂ actually removed by Virginia's preparation plants in 1983 (see Table 3.3). Not surprisingly, very high costs would have been incurred had Virginia cleaned its unwashed production: \$465 per metric tons (422 per short ton) of SO₂ removed using heavy cleaning. These costs are approximately double the corresponding costs for eastern Kentucky (see Table 4.15).

Alabama. Figure 4.5 presents the SO₂ reduction and preparation cost estimates for Alabama. Comparing this figure with those for the Central Appalachian states, some notable differences can be discerned. Unlike the Central Appalachian SO₂ content/Btu yield curves, Alabama's curves do not bend sharply towards horizontal above the 90 to 95-percent yield range; instead, the curves continue to follow a relatively pronounced downward trend with only a slight bend around the 95-percent yield point. This indicates that, for Alabama's uncleaned production, continued significant improvements in clean coal quality could be effected through continual reductions in the Btu yield point at which the coal is cleaned. For example, for both levels 2 and

Figure 4.4. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Virginia's 1983 Uncleaned Production

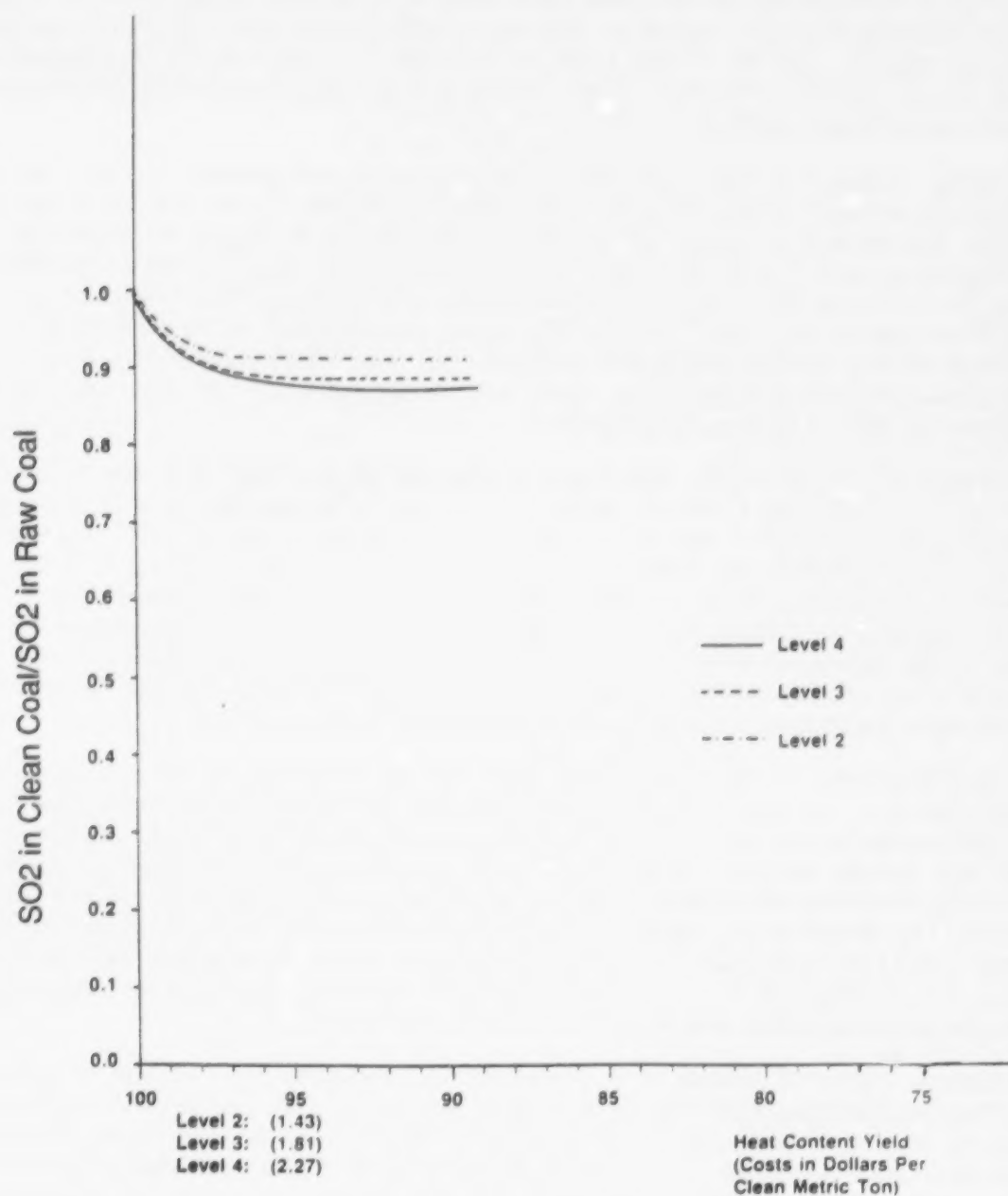


**Table 4.16. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Virginia's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	97	96
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	5,800	5,800
Total SO ₂ Reduction (Thousand Metric Tons/Year)	16	21
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.11	0.15
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	464.91	455.13

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

3, 24 percent of the total reduction in SO₂ content attainable at the 85-percent yield point occurs between the 90 and 85-percent points. Furthermore, the sharp downward trend in Alabama's curves continues past the 85-percent yield point, through the 80-percent point. Of course, at some point the Btu loss associated with continued reductions in the yield would make further reductions uneconomical. For the purposes of specifying a heavy-cleaning scenario, it has been assumed that this economic cutoff falls at a yield of 85 percent.

As a result of the unusual shape of Alabama's curves, the state's uncleaned coal, when compared with the uncleaned production for eastern Kentucky and West Virginia, appears relatively, unamenable to SO₂ reduction through cleaning at high Btu yields. For example, a product cleaned by a level 3 plant operating at a 95-percent yield would have an SO₂ content equal to 90 percent of the raw content, as compared with clean SO₂ contents of approximately 85 percent of the raw input for eastern Kentucky and West Virginia coal cleaned under the same conditions (see Figures 4.2 and 4.3). It is only at the lower Btu yields that the reduction potential for Alabama's uncleaned coal compares favorably with that for Central Appalachia's uncleaned production.

Figure 4.5 shows that there is little difference between the level 3 and level 4 curves for Alabama; this fact, combined with the significant cost difference between these two levels (\$0.56/clean metric ton (0.51/clean short ton) to \$0.66/clean metric ton (0.60/clean short ton)) suggests that the benefits to be gained by cleaning beyond level 3 would be small relative to the costs. The level 2 and level 3 curves on the other hand, diverge significantly as the yield decreases (although the divergence is not great enough to reduce level 3 costs, on a dollars per ton of SO₂ removed basis, below the level 2 costs). Therefore it was decided that level 2 was more representative of light than heavy cleaning. As mentioned previously, 85 percent was selected as the heavy cleaning yield; the light cleaning yield was set at 95 percent.

Figure 4.5. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Alabama's 1983 Uncleaned Production

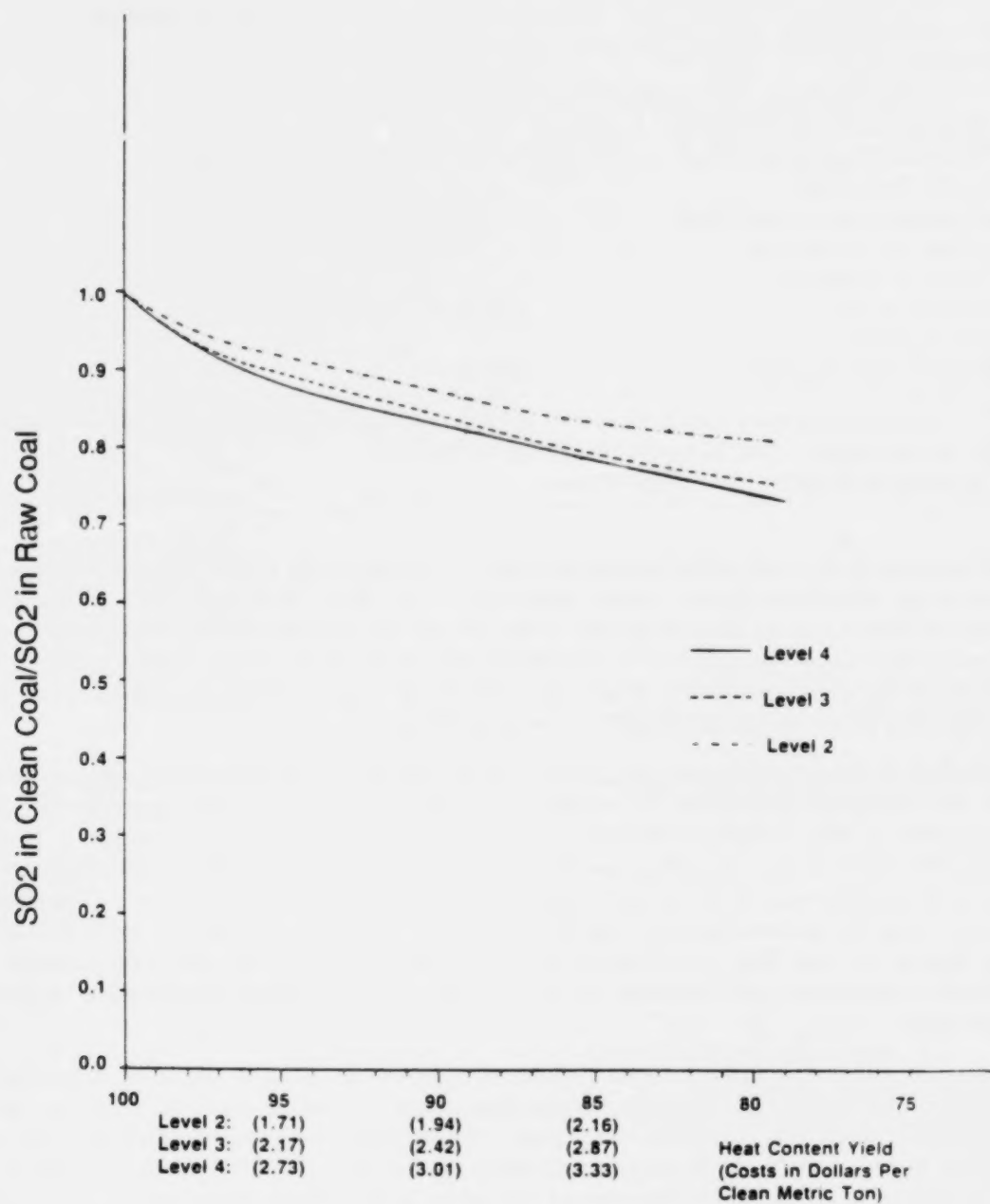


Table 4.17 presents the SO₂ reduction and cost estimates for light and heavy cleaning; as can be seen, these estimates differ substantially for the two different options. Light cleaning of the 10,900,000 metric tons (12,000,000 short tons) of uncleaned Alabama production (which represents 40 percent of the state's total 1983 production) would have resulted in the removal of 48,000 metric tons (52,900 short tons) of SO₂; heavy cleaning would have increased the SO₂ reduction to well over twice this amount. In fractional terms, the light cleaning reduction quantity represents 0.13 of the total SO₂ contained in the raw coal; this can be compared with 0.33 for heavy cleaning. Referring to Table 3.3 in the preceding chapter, the actual quantity of SO₂ removed by Alabama's cleaning plants in 1983 was 55,000 metric tons (60,600 short tons); thus even a light cleaning of Alabama's uncleaned production would have nearly doubled the state's total 1983 SO₂ reduction.

The high SO₂ reduction attainable through heavy cleaning help to reduce the preparation costs (in dollars per ton of SO₂ removed) to well below the light cleaning cost. In fact, the light cleaning costs, at \$359/metric ton (326/short ton) SO₂, are nearly double the costs of heavy cleaning. The high costs associated with light cleaning are due in part to the fact that such cleaning is relatively ineffective in reducing the SO₂ content of the coal. However, it should also be noted that, even when measured in dollars per ton of coal cleaned, Alabama's costs are relatively high compared with the preparation costs for the Central Appalachian states. For example, for a 95-percent Btu yield, level 2 costs are estimated at \$1.71/metric ton (1.55/short ton) coal (see Figure 4.5), as compared with \$1.43/metric ton (1.30/short ton) to \$1.58/metric ton (1.43/short ton) of coal for the Central Appalachian states. For heavy cleaning (i.e., level 3 cleaning at 85 percent yield), costs in dollars per ton of coal are again relatively high: \$2.67/metric ton (2.42/short ton) coal versus \$2.45/metric ton (2.22/short ton) to \$2.51/metric ton (2.28/short ton) of coal for Central

**Table 4.17. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Alabama's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	95	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	10,900	10,900
Total SO ₂ Reduction (Thousand Metric Tons/Year)	48	122
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.13	0.33
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	359.20	192.51

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Appalachian. Although the relative effectiveness of heavy cleaning in reducing the SO₂ content of Alabama's coal helps to bring the heavy cleaning costs, measured on a dollars per ton of SO₂ removed basis, down into the Central Appalachian cost range, it must be remembered that the Btu loss associated with heavy cleaning of Alabama's coal is, by definition, higher than that for Central Appalachian heavy cleaning.

Pennsylvania. Pennsylvania's SO₂ reduction/Btu yield curves, like those of Virginia and Alabama, are unique. Referring to Figure 4.6, it is evident that Pennsylvania's uncleaned coal is highly amenable to SO₂ reduction through mechanical cleaning. It is also clear that this coal is very sensitive to changes in the level of preparation. Thus cleaning the coal at level 2, with a Btu yield of 90 percent, would result in a substantial reduction in the product's SO₂ content, to 80 percent of the raw SO₂ level; but cleaning the coal at level 4 (with the yield held constant) would produce a much more substantial reduction in SO₂ content, to 62 percent of the raw level. The differences between level 3 and level 4, although less pronounced, are nonetheless quite significant. In fact, although the dollars per ton of coal cost estimates presented in Figure 4.6 increase significantly as the preparation level increases, costs for *both* levels 3 and 4 are lower than level 2 costs when measured in dollars per ton of SO₂ removed. The cost differentials between levels 2 and 3 range from a high of approximately \$30/metric ton (27/short ton SO₂, for high yields, to a low of roughly \$10/metric ton (9/short ton) SO₂ for low yields. Between levels 2 and 4 the differentials range from approximately \$5/metric ton (5.5/short ton) SO₂, at the high-yield end of the spectrum, to roughly zero for low yields. Therefore it is reasonable to use level 3, rather than level 2, as the light cleaning option for Pennsylvania, and level 4, as opposed to level 3, as the heavy cleaning option.

Like most of the curves presented thus far, Pennsylvania's drop rapidly above the 90 to 95-percent yield range, and then follow a gentler downward trend below 90 percent. Using 85 percent as the yield cutoff, it can be determined that for level 4, 74 percent of the total possible reduction in the coal's SO₂ content can be attained by cleaning at a 95-percent yield, and 90 percent of the total can be attained at a 90-percent yield. The percentages for level 3 are even higher: 78 at a 95-percent yield, and 92 at a 90-percent yield.

Although significant reduction in the SO₂ content of Pennsylvania's uncleaned coal would not be expensive in terms of Btu loss, the capital and operating costs incurred would be high, at least when measured in dollars per ton of clean coal. Comparing the cost estimates presented in Figure 4.6 with those included in Figure 4.5, it is evident that the costs of preparing Pennsylvania's uncleaned coal would be significantly higher, per ton, than cleaning Alabama's unwashed production. However, as shall soon be seen, in terms of dollars per ton of SO₂ Pennsylvania's cleaning costs are quite low.

The complete specifications for the light and heavy cleaning options, along with SO₂ reduction and preparation cost estimates associated with these options, are presented in Table 4.18. The first number worthy of note in this table is the uncleaned production total of 22,700,000 million metric tons (25,000,000 million short tons). This tonnage represents 35 percent of Pennsylvania's total 1983 production -- a substantial amount of coal, particularly in light of its amenability to SO₂ reduction through coal cleaning. As the table indicates, even a light cleaning of this coal would have increased Pennsylvania's overall SO₂ reduction by 312,000 metric tons (344,000 short tons). This would have represented a 35-percent increase in the state's actual SO₂ reduction of 894,000 metric tons (985,000 short tons) in 1983. A heavier cleaning would have produced

Figure 4.6. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Pennsylvania's 1983 Uncleaned Production

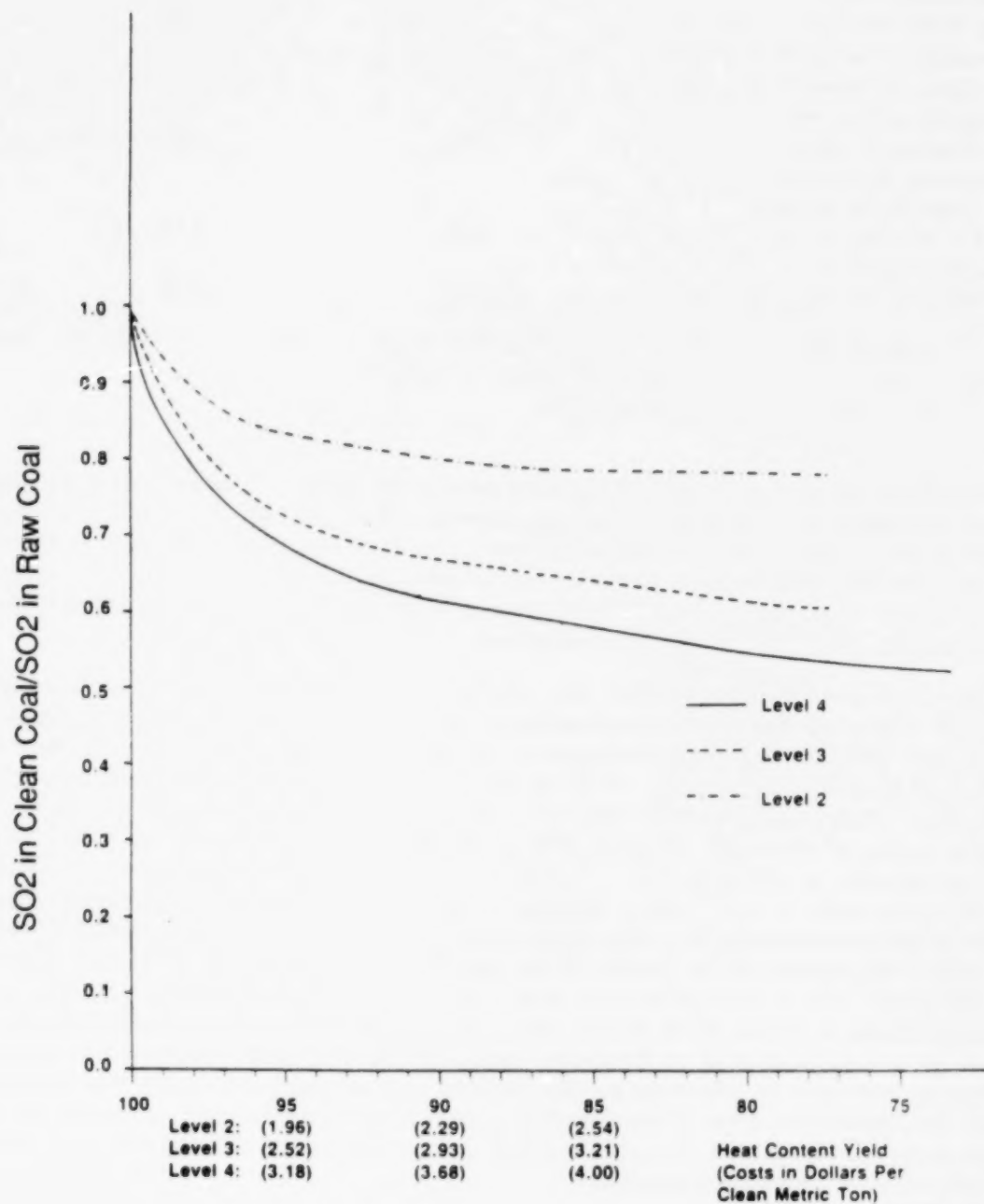


**Table 4.18. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Pennsylvania's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	3	4
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	22,700	22,700
Total SO ₂ Reduction (Thousand Metric Tons/Year)	312	443
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.31	0.44
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	167.03	139.32

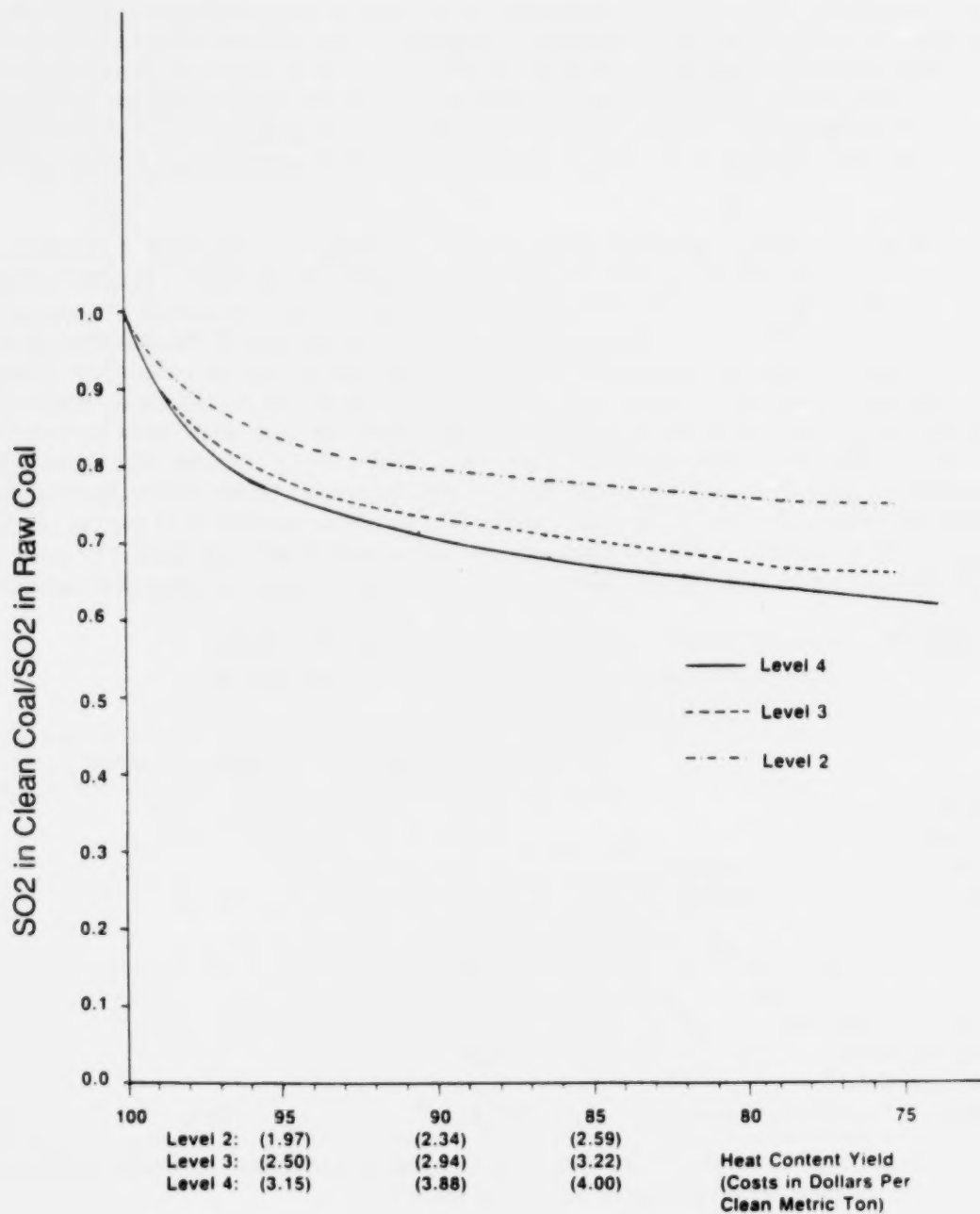
^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

443,000 additional metric tons (488,000 short tons) of rejected SO₂ -- almost half of the quantity actually rejected. In percentage terms, light cleaning would have reduced the sulfur contained in the uncleaned coal by 31 percent, while heavy cleaning would have resulted in a 44-percent sulfur reduction. Furthermore, these excellent results would have cost relatively little in terms of dollars per ton of SO₂ removed. Indeed, the cost estimates presented in Table 4.18 are the lowest per-ton-SO₂ costs for all of the states considered thus far.

Ohio. Figure 4.7 presents the SO₂ reduction/Btu yield curves for Ohio. A comparison of this figure with those presented in the preceding pages will indicate that Ohio lies somewhere between Pennsylvania and Central Appalachia in terms of the amenability of its uncleaned coal to SO₂ reduction through washing and the sensitivity of its coal to changes in the preparation level. A level 3 Ohio preparation plant operating at a Btu yield of 95 percent could have reduced the SO₂ content of the state's unwashed 1983 production to 78 percent of the raw value; the same plant operating at a 90-percent yield could have reduced the coal's SO₂ content to 73 percent of the original value. A level 2 plant, operating at the same yields, would have proved considerably less effective in reducing SO₂: such a plant would have yielded clean products with SO₂ contents equal to 84 percent and 80 percent of the raw SO₂ content, at yields of 95 and 90 percent, respectively. The differences between level 3 and level 4 are less pronounced, but they are not insignificant; at a yield of 95 percent the clean SO₂ content would have been reduced to 76 percent of the raw level; at the 90-percent yield point, this percentage would have dropped to 70 percent. Although the differences between the level 3 and 4 estimates are larger than was the case for the Appalachian states, it was nonetheless decided that level 3 should be selected for heavy cleaning, in keeping with the general conservative policy used in defining the heavy cleaning options for the uncleaned production.

Figure 4.7. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Ohio's 1983 Uncleaned Production



As with the curves for most of the other states covered thus far, Ohio's SO₂ reduction/Btu yield curves follow a sharp downward trend above the 90 to 95 percent yield range and then begin to flatten out below the 90-percent point. Of the total reduction in SO₂ content attainable through level 3 cleaning between yields of 100 percent and 85-percent, 73 percent is attainable at a 95-percent yield and 90 percent is attainable at the 85-percent yield point. The percentages for level 2 are similar. With regard to preparation costs, Ohio is very similar to Pennsylvania; a comparison of the cost estimates presented in Figures 4.6 and 4.7 will indicate that the cost differentials between the two states fall in the \$0.00 to \$0.05/clean ton range. Thus, the costs of preparing Ohio's uncleaned coal, when measured on a dollars per ton of coal basis, would (like the costs for Pennsylvania) be high. However, when measured in dollars per ton of SO₂ removed, Ohio's costs are extremely low, even when compared with Pennsylvania's low per-ton-SO₂ costs.

Heavy cleaning of Ohio's uncleaned production was specified as being level 3 cleaning at a 90-percent Btu yield; level 2 cleaning at a yield of 95 percent was selected as the light cleaning option. The SO₂ reduction and cost estimates corresponding to these two options are presented in Table 4.19. As this table shows, Ohio produced 6,100,000 metric tons (6,700,000 short tons) of uncleaned coal in 1983; this represented 18 percent of the state's total raw production. Cleaning this coal using the light option would have yielded 84,000 metric tons (93,000 clean tons) of SO₂ in the refuse (or 20 percent of the SO₂ in the raw coal). Heavy cleaning would have increased this total to 142,000 metric tons (157,000 clean tons) (34 percent of the raw SO₂ quantity). A comparison of these totals with the actual quantity of SO₂ removed by the state's cleaning plants in 1983 will indicate that they represent a potential SO₂ reduction increase of 11 percent (for light cleaning) and 19 percent (for heavy cleaning) of Ohio's current SO₂ reduction. The costs that would be incurred in reaching the light or heavy potentials would be quite low relative to

**Table 4.19. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Ohio's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	6,100	6,100
Total SO ₂ Reduction (Thousand Metric Tons/Year)	84	142
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.20	0.34
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	132.33	108.61

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

cleaning costs for other states, when measured on a dollars per ton of SO₂ removed basis. In fact, the cost estimates presented in Table 4.19 are approximately \$30 to \$35 lower than the corresponding costs for Pennsylvania.

Illinois. Figure 4.8 presents the SO₂ reduction and preparation cost estimates for Illinois. As the figure shows, Illinois's SO₂ reduction/Btu yield curves drop sharply above the 95-percent yield point, and then follow a gentler, linear downward trend through the 85-percent point. Although the slopes of the curves are lower below the 95-percent point than above, they are nonetheless high compared with the slopes (below the 95 percent yield point) for most of the other states. In fact, Illinois's curves are almost as steep as those of Alabama below the 95-percent point. However, because Illinois's curves also follow a sharp downward trend above the 95 percent point, whereas Alabama's do not, the relative improvements in the quality of the clean coal attainable through continued reductions in the Btu yield are smaller for Illinois than for Alabama. For example, for level 3 cleaning, only 13 percent of the total reduction in SO₂ content attainable by washing at an 85-percent yield occurs between the 90 and 85 percent yield points; the corresponding percentage for Alabama is 24. Indeed, fully 73 percent of the total possible SO₂ content reduction (using 85 percent as the yield cutoff) can be attained by washing at a 95 percent yield. Therefore, instead of selecting 85 percent as the heavy cleaning yield (as was done for Alabama), 90 percent was instead chosen as representing a reasonable cost/benefit tradeoff for coal not being cleaned at present.

With regard to its overall amenability to SO₂ reduction through washing, Illinois's uncleaned coal is very similar to the unwashed portion of Ohio's production. At level 2, and a yield of 95 percent, a plant processing Illinois's uncleaned coal could reduce the coal's SO₂ content to 83 percent of the raw value (as opposed to 84 percent for Ohio); the same plant, operating at a 90-percent yield, could bring the clean coal SO₂ content down to 74 percent of the raw value (versus 73 percent for Ohio). Illinois's coal is also similar to Ohio's in its relative sensitivity to changes in the level of preparation. In fact, the improvement in SO₂ reduction achievable by switching from level 2 to level 3 is such that the costs of cleaning at level 3, measured on a dollars per ton of SO₂ removed basis, are nearly equal to the level 2 cleaning costs. (This same situation, it should be noted, exists for Ohio.) However, the additional improvements in real quality attainable through a further increase in the preparation level (to level 4) are less pronounced and do not quite match the corresponding improvements for Ohio.

The costs associated with cleaning Illinois's unwashed production, measured on a dollars per clean ton basis, are quite high relative to the corresponding costs for the Appalachian states. Even when compared with the estimates for a "high cost" state such as Pennsylvania or Ohio, Illinois's cost estimates are typically \$0.25/clean metric ton (0.23/clean short ton) to \$0.40/clean metric ton (0.36/clean short ton) higher for corresponding preparation levels and Btu yields. However, as was the case for these Northern Appalachian states, the relatively large SO₂ reductions attainable through cleaning Illinois's coal works to reduce costs, measured in dollars per ton of SO₂ removed, to relatively low levels.

Table 4.20 presents the specifications for light and heavy cleaning of Illinois's unwashed production, along with the corresponding SO₂ reduction and cleaning costs estimates. As the table indicates, Illinois produced 4,100,000 metric tons (4,500,000 short tons) of coal in 1983; this represented only 7 percent of the state's total raw tonnage. For this reason, the additional SO₂ reduction attainable by washing this coal is fairly small relative to the SO₂ reduction that the state

Figure 4.8. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Illinois' 1983 Uncleaned Production

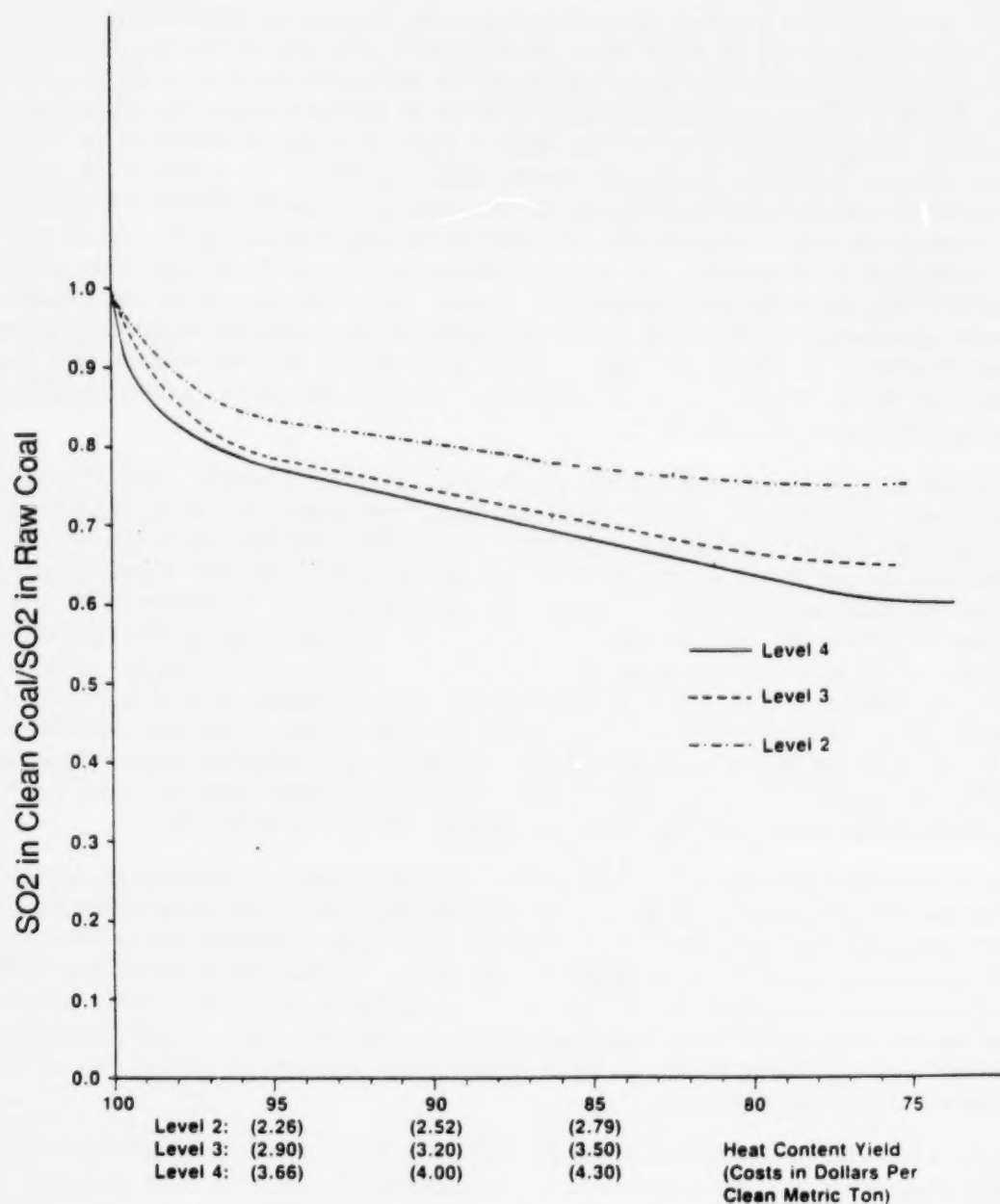


**Table 4.20. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Illinois' Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	4,100	4,100
Total SO ₂ Reduction (Thousand Metric Tons/Year)	54	85
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw) ^b	0.21	0.33
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	155.46	129.35

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

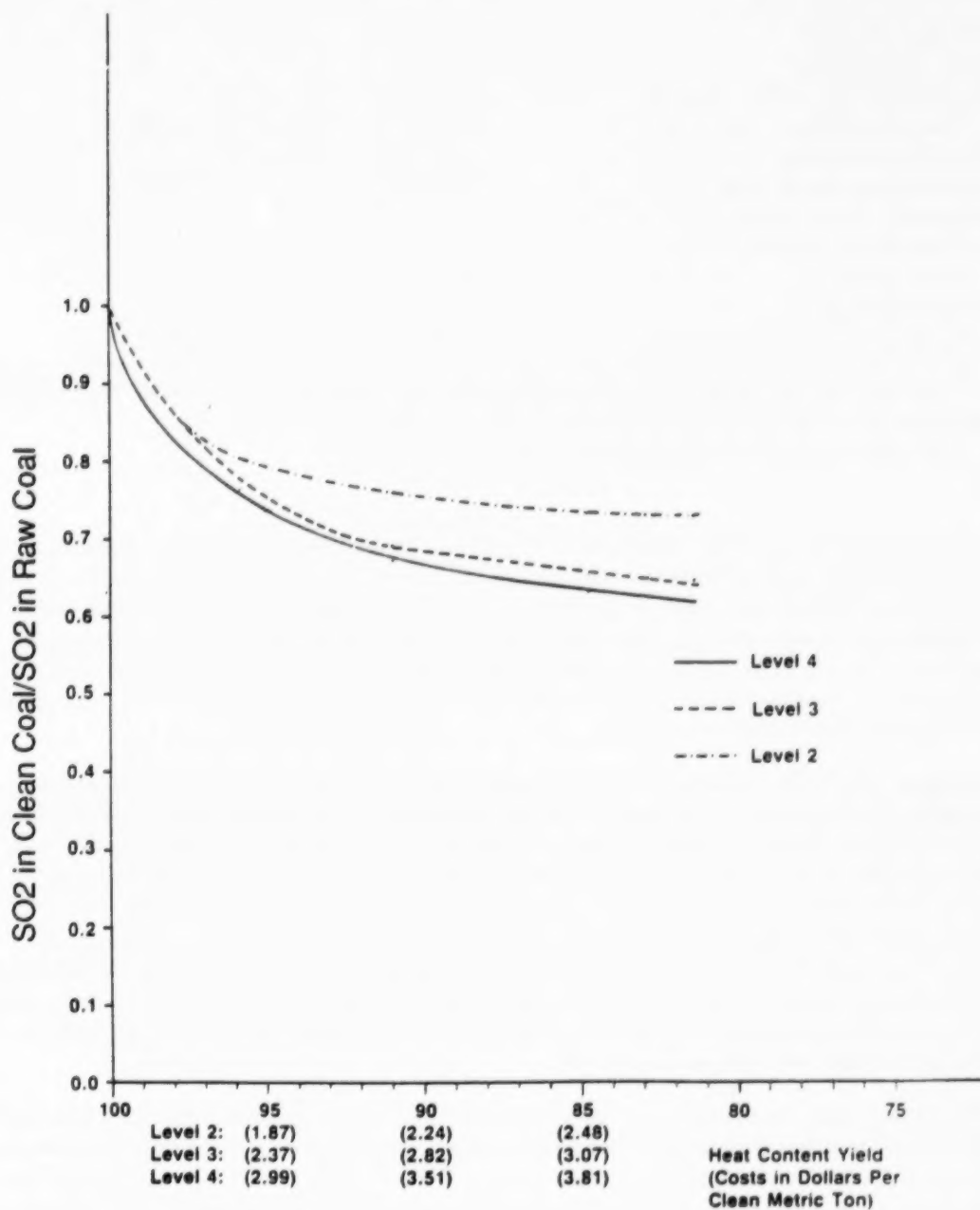
^bIncludes both capital and operating costs.

actually achieved in 1983. Referring to Table 3.3 in the preceding chapter, Illinois's cleaning plants removed 1,463,000 metric tons (1,613,000 short tons) of SO₂ from the state's raw 1983 production. Even if the 4 million metric tons (4.4 million short tons) of uncleaned coal had been subjected to heavy cleaning, the total SO₂ reduction would have been increased by only 6 percent. On the other hand, the cost of this slight improvement in the state's overall SO₂ reduction, in dollars per ton of SO₂ removed, would have been relatively low -- approximately \$130/metric ton (118/short ton) SO₂.

Indiana. The SO₂ reduction and preparation cost estimates for Indiana's uncleaned coal are presented in Figure 4.9. This figure indicates that Indiana's unwashed coal is highly amenable to SO₂ reduction through cleaning. Indiana's coal is in fact considerably more responsive to level 2 cleaning than is Pennsylvania's uncleaned product. For example, at a 90-percent yield, a level 2 plant could reduce the SO₂ content of Indiana's coal to 75 percent of the raw SO₂ content; the same plant, operating at the same yield, would reduce the SO₂ content of Pennsylvania's coal to only 80 percent of the raw value. Furthermore, although the SO₂ reduction potential represented by Indiana's unwashed product cannot match that of Pennsylvania's uncleaned coal, it exceeds, by a significant amount, the reduction potential of other highly washable coals (such as Illinois and Ohio coals) at all preparation levels.

The slopes (and the changes in the slopes) of Indiana's SO₂ reduction/Btu yield curves are similar to these for most of the other eastern states. Likewise, the relationships between the three curves follow the typical pattern: the level 3 and level 4 curves track fairly closely together, while the level 2 curve diverges significantly from the curve for level 3. Finally, with regard to costs, Indiana compares favorably with both Illinois and the Northern Appalachian states. And, as was the case for Illinois and Ohio, Indiana's cost estimates, in dollars per ton of SO₂ removed, are

Figure 4.9. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Indiana's 1983 Uncleaned Production



nearly equal for levels 2 and 3. (The cost differences between the two levels range from approximately \$3.00/metric ton (2.72/short ton) SO₂ for low yields to \$5.00/metric ton (4.54/short ton) SO₂ for high yields.)

Table 4.21 presents the selected preparation level and Btu yield specifications for light and heavy cleaning, and the corresponding SO₂ reduction and cleaning cost estimates. The "quantity of coal to be cleaned" -- 7,500,000 metric tons (8,300,000 short tons) -- represents 22 percent of Indiana's total raw production for 1983. Due to the relative amenability of the coal to washing, the SO₂ reduction estimates, even for light cleaning, are relatively high. Furthermore, the costs of achieving these substantial gains, measured on a dollars per ton of SO₂ removed basis, would have been extremely low -- the lowest, in fact, of all the states considered thus far.

Western Kentucky. Figure 4.10 presents the SO₂ reduction and preparation cost estimates for western Kentucky's uncleaned coal. The figure indicates that, at level 3 preparation and a Btu yield of 95 percent, the SO₂ content of this coal could be reduced to 78 percent of the raw value; decreasing the yield to 90 percent would result in a further reduction of the SO₂ content to 72 percent of the original value. For level 2 preparation, the corresponding SO₂ content reduction percentages, at yields of 95 and 90 percent, are 83 and 79, respectively. A comparison of these percentages with the corresponding percentages for Ohio will show that they are nearly equivalent. Western Kentucky's curves are very similar to Ohio's in a number of other respects as well: both sets of curves are characterized by approximately the same slopes (and changes in slopes), and the SO₂ content reduction differentials between levels 2, 3 and 4 are approximately equal for the two sets of curves. However, with regard to costs, the two regions are less similar: western Kentucky's cost estimates range from approximately \$0.10/clean metric ton (0.09/clean short ton) to \$0.25/clean metric ton (0.23/clean short ton) higher than those of Ohio. Yet, in terms of dollars per ton of SO₂ removed, western Kentucky's cost estimates are somewhat lower than

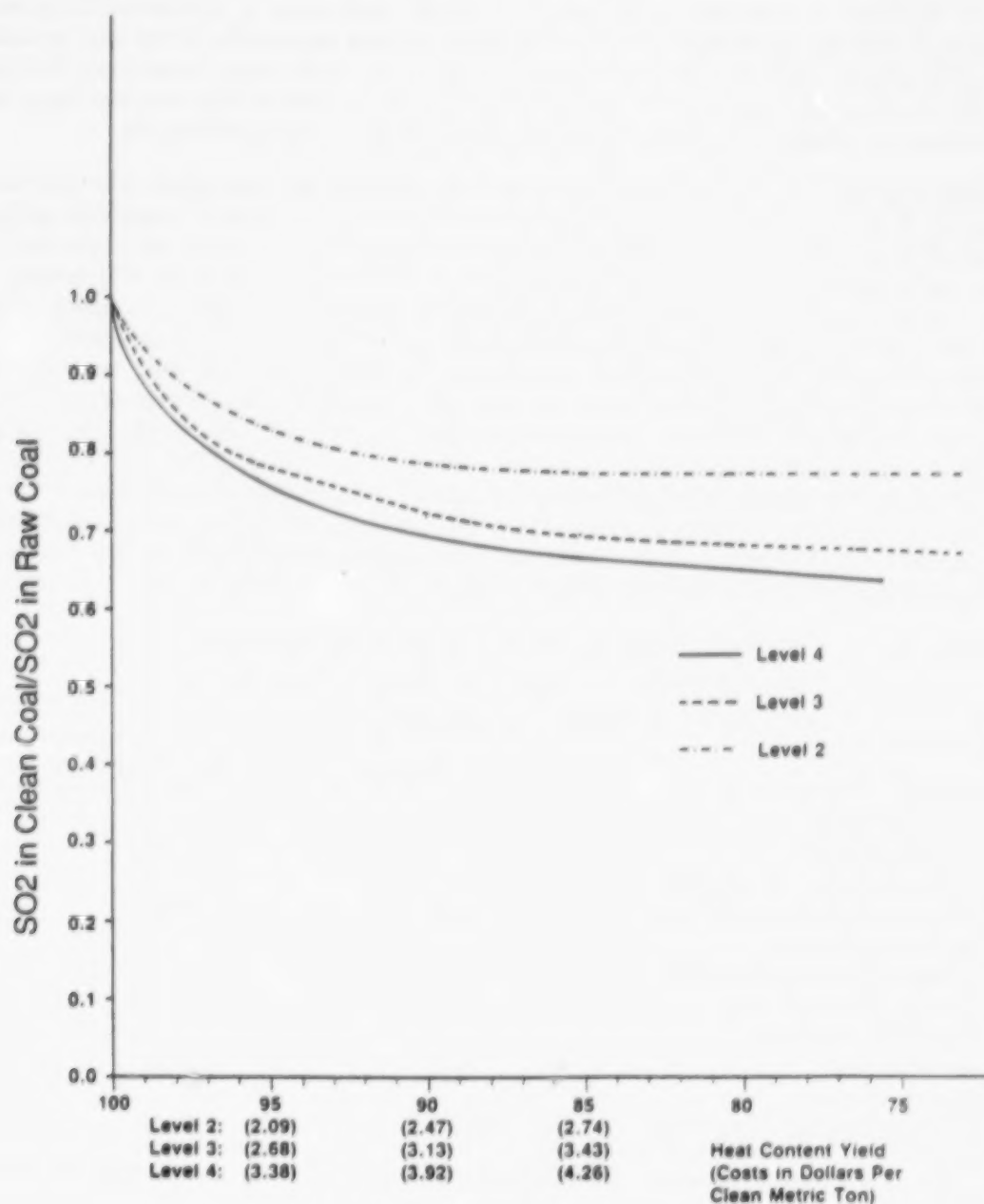
**Table 4.21. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Cleaning of
Indiana's Uncleaned Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	7,500	7,500
Total SO ₂ Reduction (Thousand Metric Tons/Year)	130	198
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.25	0.38
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	100.12	92.40

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Figure 4.10. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Western Kentucky's 1983 Uncleaned Production



Ohio's. And, as was the case for Ohio and other Midwestern states, the differentials between level 2 and level 3 costs, in a dollars per ton of SO₂, are very small.

Table 4.22 presents the specifications selected for the light and heavy cleaning options, along with the SO₂ reduction and preparation cost estimates corresponding to these options. As can be seen, western Kentucky produced 10.4 million metric tons (11.5 million short tons) of uncleaned coal in 1983; this represented 17 percent of the region's total raw production for the year. Had this coal been subjected to a light cleaning, 169,000 tons (186,000 short tons) of SO₂ (or 21 percent of the total SO₂ in the raw coal) could have been removed from it. This would have resulted in a 20-percent increase in western Kentucky's total SO₂ reduction for 1983. A heavy cleaning of the unwashed product would have increased the region's overall reduction by 33 percent. The costs associated with these increases, in dollars per ton of SO₂ removed, would have been relatively low -- indeed, almost as low as the light and heavy cleaning costs for Indiana's unwashed production (see Table 4.20).

Clean 1983 Production

West Virginia. Figure 4.11 presents the SO₂ reduction/Btu yield curves for West Virginia's clean 1983 production. A comparison of this figure with Figure 4.2 (which presented the corresponding curves for West Virginia's uncleaned coal) reveals a sharp contrast between the two: the clean coal curves follow a much more pronounced downward trend than do the curves for uncleaned production. The difference in the slopes of the two curves is not surprising: it indicates that the coal currently being cleaned is more amenable to washing than is the uncleaned coal. West Virginia preparation plant operators thus appear to be concentrating their efforts where they will do the most good.

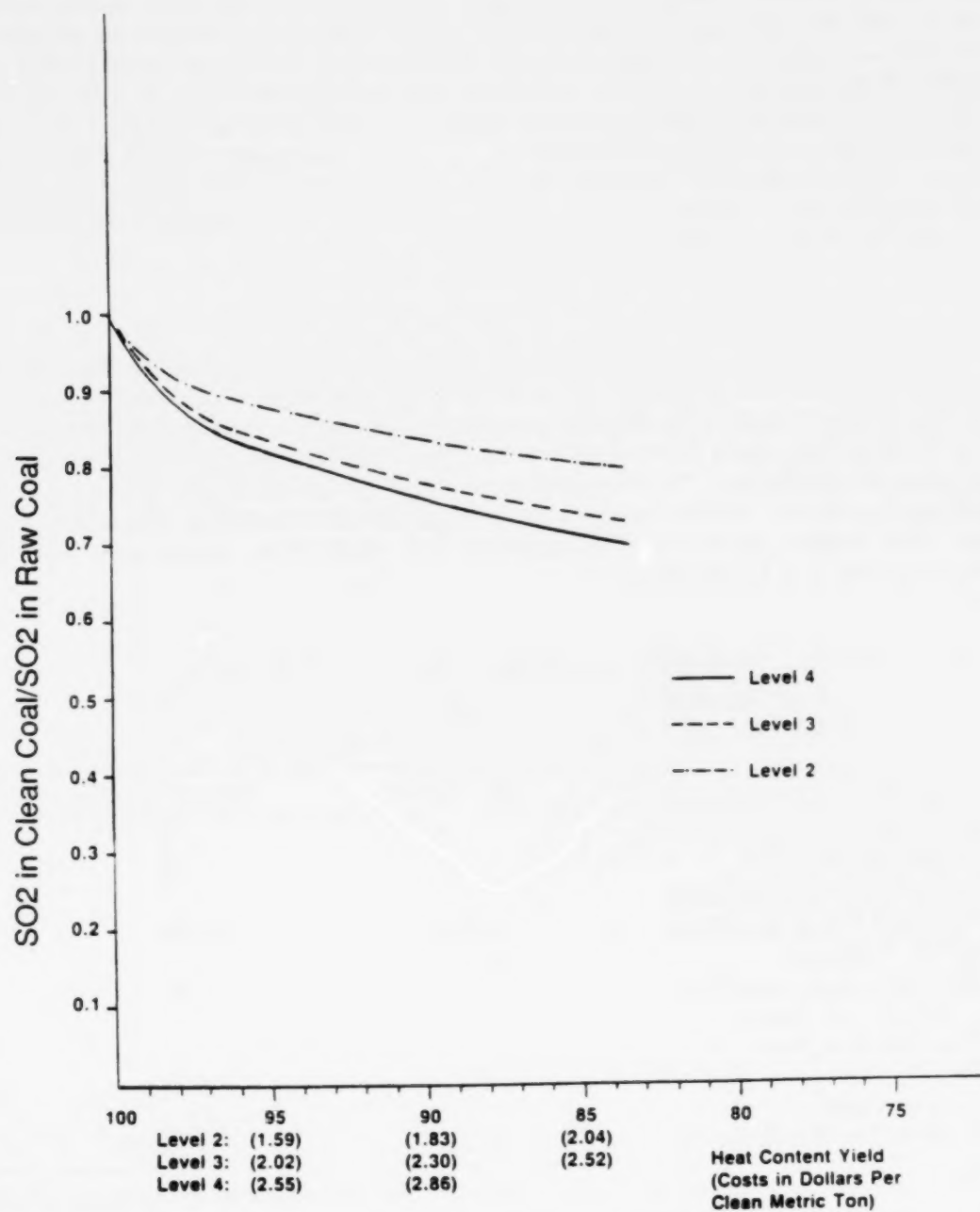
Table 4.22. SO₂ Reduction and Preparation Cost Estimates Corresponding to Light and Heavy Cleaning of Western Kentucky's Uncleaned Production^a

	Light Cleaning	Heavy Cleaning
Preparation Level	2	3
Btu Yield (Percent)	95	90
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	10,400	10,400
Total SO ₂ Reduction (Thousand Metric Tons/Year)	169	281
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Ton SO ₂ Raw)	0.21	0.35
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	118.20	98.58

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Figure 4.11. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for West Virginia's Clean Production



It is important to note that the differences in the slopes of the two sets of curves increase as the yield decreases. Thus, at the lower yields, one finds that the clean coal curves have unusually large slopes (see Figure 4.5). This fact suggests that substantial improvements in West Virginia's current SO₂ reduction can be attained, at relatively low costs, by decreasing the Btu yield at which West Virginia's plants are operating. Additional improvements can, of course, also be obtained by increasing the level at which the plants operate. Figure 4.11 indicates that the potential gains that would result from converting level 2 plants to level 3 are quite significant; however, converting level 3 plants to level 4 would yield less substantial improvements.

How large would the increase in SO₂ reduction resulting from these changes be, and how much would it cost to effect the change? An approximate answer can be obtained by locating the current SO₂ reduction estimate for West Virginia on the SO₂ reduction/Btu yield curves. Since West Virginia's cleaning plants do not all operate at the same preparation level, the selection of a single point on one of the curves as being "the" point at which West Virginia is currently operating will obviously be an oversimplification; nonetheless, if the point is selected carefully, it should enable the development of reasonable approximations of the potential for further reductions in SO₂ through higher-intensity cleaning.

Referring to Table 3.3 of the preceding chapter, it can be determined that West Virginia's cleaning plants removed 34 percent of the total quantity of SO₂ input to the plants in 1983. It appears that West Virginia relied primarily on level 4 cleaning to achieve these results; however, the state also retains a significant number of level 3 plants as well as a few level 2 plants. Thus, to take into account the impact of the plants operating at the lower levels, the state's current SO₂ reduction point was located on the level 3 curve. After converting the current reduction estimate from fractional tons SO₂ to fractional tons per million Btu, it was found that it falls at approximately the 88-percent Btu yield point on the curve.

To estimate the potential for increasing West Virginia's SO₂ reduction through more intensive cleaning, the practice of specifying two possible cleaning options, followed throughout the preceding subsection to estimate the reduction potential for uncleaned coal, was employed once again. However, since the costs associated with converting an existing plant from one preparation level to another, or changing the yield at which an existing plant is operating, are considerably lower than the costs of building and operating a new plant, the specifications for the "light additional cleaning" and "heavy additional cleaning" options used to develop potential reduction estimates for West Virginia's clean coal were selected to be less conservative than the light cleaning and heavy cleaning specifications used to estimate the potential reduction for uncleaned coal. Thus, whereas light cleaning was typically set at level 2, and heavy cleaning at level 3, throughout the last subsection, for West Virginia's clean product (as well as the clean coal for the states covered in the following pages) level 4 cleaning was chosen for both light additional and heavy additional cleaning. Also, whereas in the preceding subsection 95 and 90 percent were typically used as the yields for light and heavy cleaning, respectively, here the light additional cleaning yield was set equivalent to the yield corresponding to the location of the current SO₂ reduction point on the curve (88 percent -- see above), while 85 percent was chosen as the heavy additional cleaning yield.

Table 4.23 presents the estimates of the increases in SO₂ reduction attainable through light additional and heavy additional cleaning, along with estimates of the costs associated with the increases. As can be seen, light additional cleaning is relatively ineffective; its application would

**Table 4.23. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
West Virginia's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	88	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	96,100	96,100
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	60	197
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.02	0.07
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.03	0.10
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	727.38	264.74
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.54	0.67

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

have increased the 1983 SO₂ reduction by 60,000 metric tons (66,000 short tons). This tonnage figure represents only 2 percent of the SO₂ in the raw coal, or 3 percent of the SO₂ remaining in the coal after cleaning and before additional cleaning. On the other hand, the SO₂ reduction increases attainable through heavy additional cleaning appear more significant -- particularly when the increases are measured as a percentage of the SO₂ content of the clean coal. A comparison of the reduction estimates presented in Table 4.23 with those presented in Table 4.14 will indicate that West Virginia's uncleaned coal represents greater SO₂ reduction potential than does the state's clean product. Even a light cleaning of the uncleaned coal would result in a larger SO₂ reduction increase than heavy additional cleaning of the clean coal (226,000 metric tons (249,000 short tons) of SO₂ removed for light cleaning versus 197,000 metric tons (217,000 short tons) of coal removed for heavy additional cleaning). This is the case despite the fact that the quantity of coal cleaned (96,100,000 metric tons (105,900,000 short tons)) is nearly four times as large as the quantity of uncleaned coal.

The cost estimates presented in Table 4.23 represent the sum of two components:

- The difference in estimated operating costs between a plant operating under the specified light or heavy conditions and a plant operating at level 3 and a Btu yield of 88 percent (the point corresponding to the state's current SO₂ reduction level -- see preceding discussion).

- The difference in the capital costs associated with purchasing and installing cleaning equipment for a level 4 plant (operating at an 88-percent or 85-percent yield) and the corresponding capital costs for a level 3 plant (operating at an 88-percent yield). As can be seen, the cost estimates, when measured on a dollars per ton of clean coal basis, are quite low. This, of course, reflects the fact that the capital expenditure that would be incurred in modifying an existing plant would be considerably less than the capital cost associated with building a new plant. But, when costs are measure on a dollars per ton of SO₂ removed basis, they appear quite large. This is especially true of the light additional cleaning costs; but even the heavy additional cleaning costs, when compared with the corresponding costs for West Virginia's uncleaned coal (see Table 4.14), prove high. In fact, the heavy additional cleaning costs exceed, by a significant amount, the cost estimates for light cleaning of the uncleaned coal (\$198.14/metric ton (179.75/short ton) SO₂ for light cleaning, versus \$284.74/metric ton (258.31/short ton) for heavy cleaning). Thus the costs associated with additional cleaning of West Virginia's clean coal are greater than the costs of cleaning the state's uncleaned product.

Eastern Kentucky. Figure 4.12 presents the SO₂ reduction/Btu yield curves for eastern Kentucky's clean production. Comparing these curves with the corresponding curves for the region's uncleaned coal, one finds that they are very dissimilar. In fact, except at low yields of approximately 85 percent or less, the *level 2* curve for clean coal falls at lower SO₂ content points than the *level 4* curve for the uncleaned coal. Clearly, eastern Kentucky plant operators, even more than their West Virginia counterparts, are selecting that portion of the raw production most amenable to cleaning for use as input to their preparation plants.

In addition to the difference in the general positions of the clean and uncleaned coal curves with respect to the y-axis, there are some other notable differences between the two sets of curves. For one, the degree of difference between the curves for the different preparation levels is considerably larger for the clean than for the uncleaned coal. Indeed, even the level 3 and 4 curves diverge fairly significantly (at the lower yields) for the clean coal; this suggests the possibility that significant improvements in eastern Kentucky's current SO₂ reduction might be obtained by converting level 2 and 3 plants to level 4. Also, whereas the uncleaned coal curves continue to follow a downward trend through the 85 percent yield point, the clean coal curves reach a minimum in the 86 to 89-percent range, and then bend upward (indicating that beyond this range the Btu loss exceeds the sulfur reduction). Thus, it appears that while significant improvements in reduction might be achieved by increasing the level at which eastern Kentucky's plants operate, little improvement can be expected by reducing the yields at which the plants are operating (except in the case of those plants operating well above the 86 to 89-percent range).

As was discussed in Chapter 3, the current SO₂ reduction estimate for eastern Kentucky was adjusted so that it could be located at a reasonable point on the clean coal curves. The adjusted estimate was selected so that it would fall on the level 3 curve, at a Btu yield of 89 percent. Based on this current SO₂ reduction point, level 4 cleaning was specified for both the light and the heavy cleaning options; the yield specifications, SO₂ reduction estimates, and cost estimates corresponding to the options are presented in Table 4.24. As can be seen, neither light nor heavy additional cleaning can be expected to produce much improvement in SO₂ reduction. To put the Table 4.24 estimates in perspective, the corresponding light and heavy reduction estimates for the region's uncleaned coal are 132,000 metric tons (145,500 short tons) and 218,000 metric tons (240,300 short tons), respectively. The large differences between the clean coal and uncleaned

Figure 4.12. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Eastern Kentucky's Clean Production

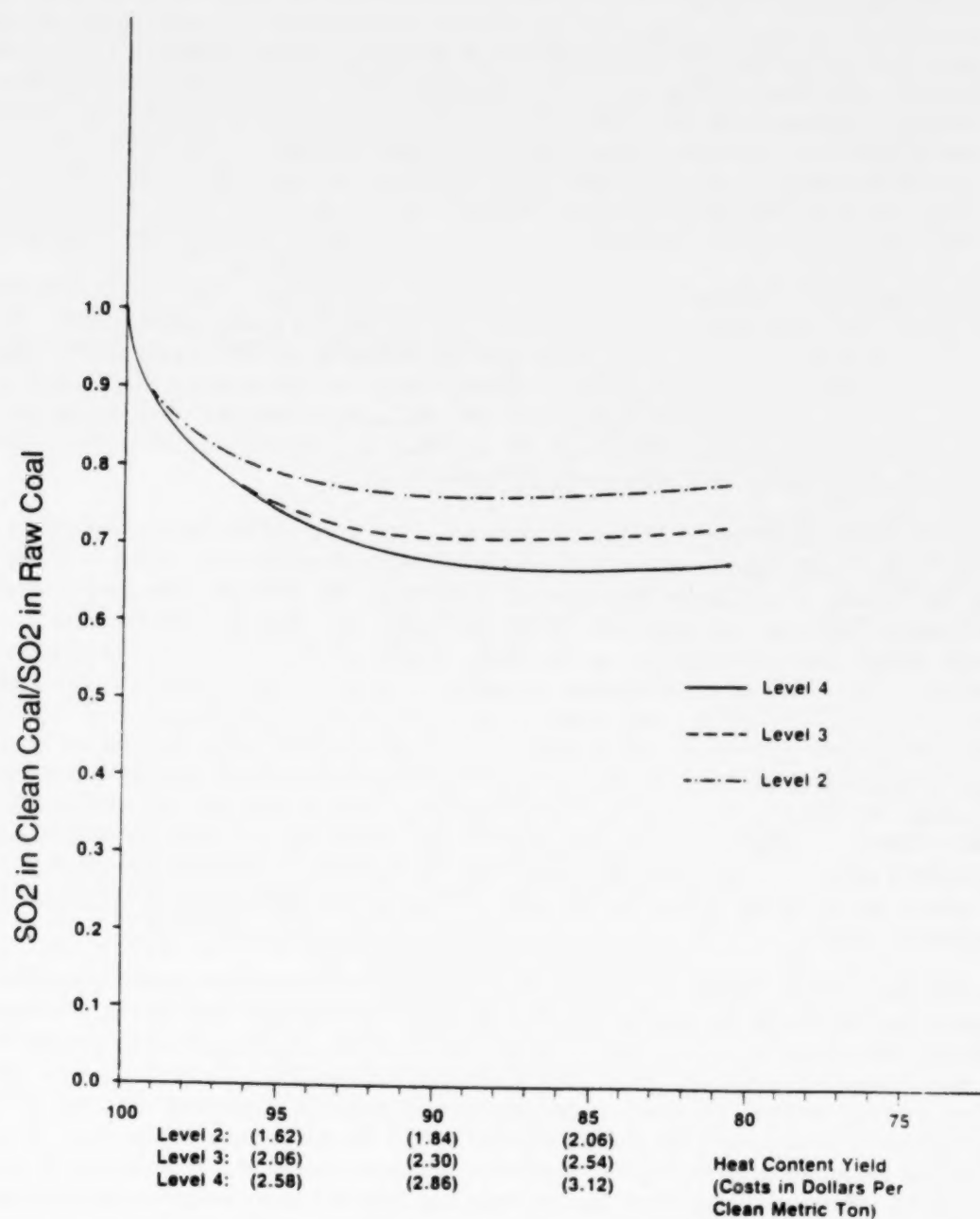


**Table 4.24. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Eastern Kentucky's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	89	86
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	29,100	29,100
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	13	22
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.03	0.05
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.05	0.08
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	1,018.16	707.21
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.55	0.67

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

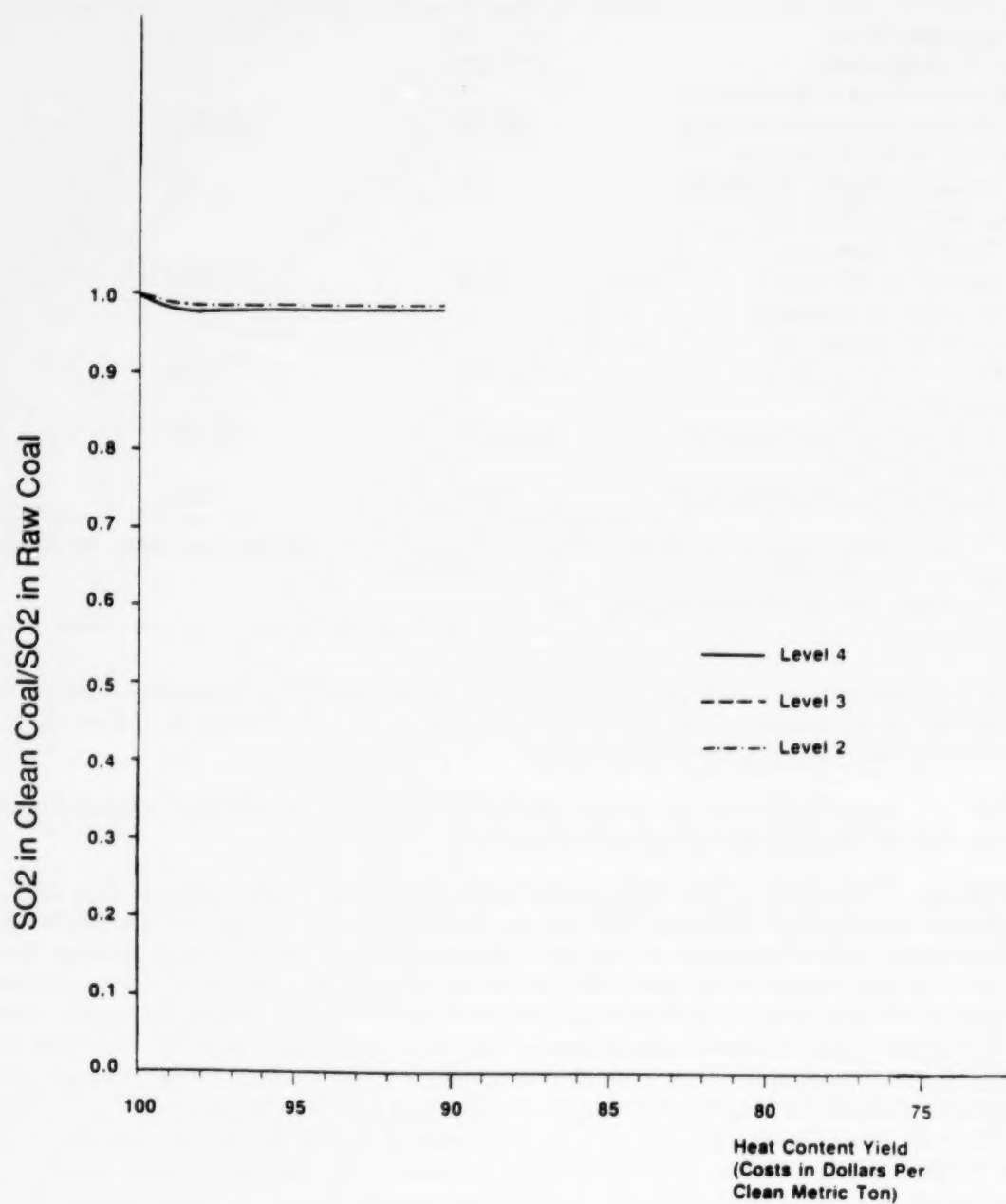
^bIncludes both capital and operating costs.

coal reduction estimates is in part a reflection of the fact that eastern Kentucky is producing a relatively large quantity of uncleaned coal. In 1983, fully 43 percent of the region's raw production was shipped without any cleaning.

Table 4.24 also indicates that the costs of light additional and heavy additional cleaning would be quite high, at least in dollars per ton of SO₂ removed.

Virginia. Virginia is a state that presents analysis problems. The potential SO₂ reduction estimates are presented in Figure 4.13. As can be seen, the figure suggests that essentially no improvement in the SO₂ content of Virginia's clean coal can be gained through washing. Even at level 4, the SO₂ content of the clean coal can, at best, be reduced to 98 percent of the raw value. Although the SO₂ reduction/Btu yield curves for the state's uncleaned production also indicate that Virginia coal is relatively unamenable to SO₂ reduction through washing, they nonetheless indicate that some improvement in clean coal quality is possible. Furthermore, the current SO₂ reduction estimate for Virginia (See Chapter 3, Table 3.2) likewise indicates that the SO₂ content of the state's coal can, at least to some degree, be reduced. In fact, the current reduction estimate for Virginia falls outside the range of the curves in Figure 4.13. It should be noted, however, that the current SO₂ reduction estimate for Virginia was derived, from a very small sample of plants (3), and therefore, it may itself be inaccurate. Nonetheless, while the state's current SO₂ reduction may, to some degree, be overestimated, the fact remains that the potential SO₂

Figure 4.13. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Virginia's Clean Production



reduction curves for Virginia's uncleaned coal also indicate that the state's reserves are not totally unresponsive to cleaning.

It is believed that the potential reduction estimates for Virginia's clean coal are based on an inadequate number of unrepresentative washability samples. Furthermore, given that the state's coal is clearly relatively unamenable to cleaning, and that the current reduction estimate for Virginia (see Table 3.2) is fairly high given this lack of amenability to cleaning, it is believed that the quantity of SO₂ removable through more intensive washing would be very small -- indeed, insignificant. Therefore, one would not be far off in assuming that the additional SO₂ reduction attainable through light additional or heavy additional cleaning of Virginia's clean product is zero.

Alabama. Figure 4.14 presents the SO₂ reduction and preparation cost estimates for Alabama's clean coal. Interestingly, when the curves in this figure are compared with those in Figure 4.5 (for Alabama's uncleaned coal), it is found that Alabama's clean coal is less amenable to SO₂ reduction through washing than the state's uncleaned coal. In fact, the level 2 curve for uncleaned coal corresponds more closely to the level 4 clean coal curve than to the level 2 curve. Unlike the Central Appalachian states, Alabama is concentrating its preparation efforts on that portion of its production that is relatively difficult to clean.

Other than the differences in the positions of the clean and uncleaned curves with respect to the y-axis, the two sets of curves are fairly similar; e.g. the differentials separating the curves for different preparation levels are approximately equal across the two sets. To determine the increases in SO₂ reduction attainable through light additional and heavy additional washing of the state's clean product, the current reduction estimate was located on the clean coal curves. It was found that, at level 3 cleaning, the current estimate falls at approximately the 94-percent Btu yield point. Light additional cleaning was specified as being level 4 cleaning at a 90-percent yield, whereas heavy additional cleaning was set at 85 percent. The increases in SO₂ reduction attainable under these operating conditions, along with the costs Figure 4.13 associated with these increases, are presented in Table 4.25. A comparison of Table 4.25's SO₂ reduction estimates with the current reduction estimate of 55,000 metric tons (61,000 short tons) indicates that substantial improvements can be made through more intensive cleaning. This is a result of the fact that Alabama's preparation plants are currently operating at a relatively high yield: most of the increase in SO₂ reduction attainable through light additional or heavy additional cleaning is caused by the change in yield rather than the change in preparation level. The costs of improving SO₂ reduction are somewhat high (relative to the corresponding costs for the Central Appalachian states) when measured in dollars per ton of coal; however, in dollars per ton of SO₂ removed they compare favorably with the Central Appalachian costs.

Pennsylvania. A comparison of Figure 4.15 (which represents the SO₂ reduction/Btu yield curves for Pennsylvania's clean coal) with Figure 4.6 (which presents the corresponding curves for Pennsylvania's uncleaned product) will indicate that the two figures are very similar. There are only two differences worth noting. First, the level 3 and 4 curves for clean coal follow a slightly lower path than their uncleaned coal counterparts, indicating that the clean coal is slightly more amenable to washing. And second, the cost estimates for the clean coal are typically \$0.05/metric ton (0.05/short ton) coal to \$0.15/metric ton (0.14/short ton) coal higher than the uncleaned coal estimates.

Figure 4.14. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Alabama's 1983 Clean Production

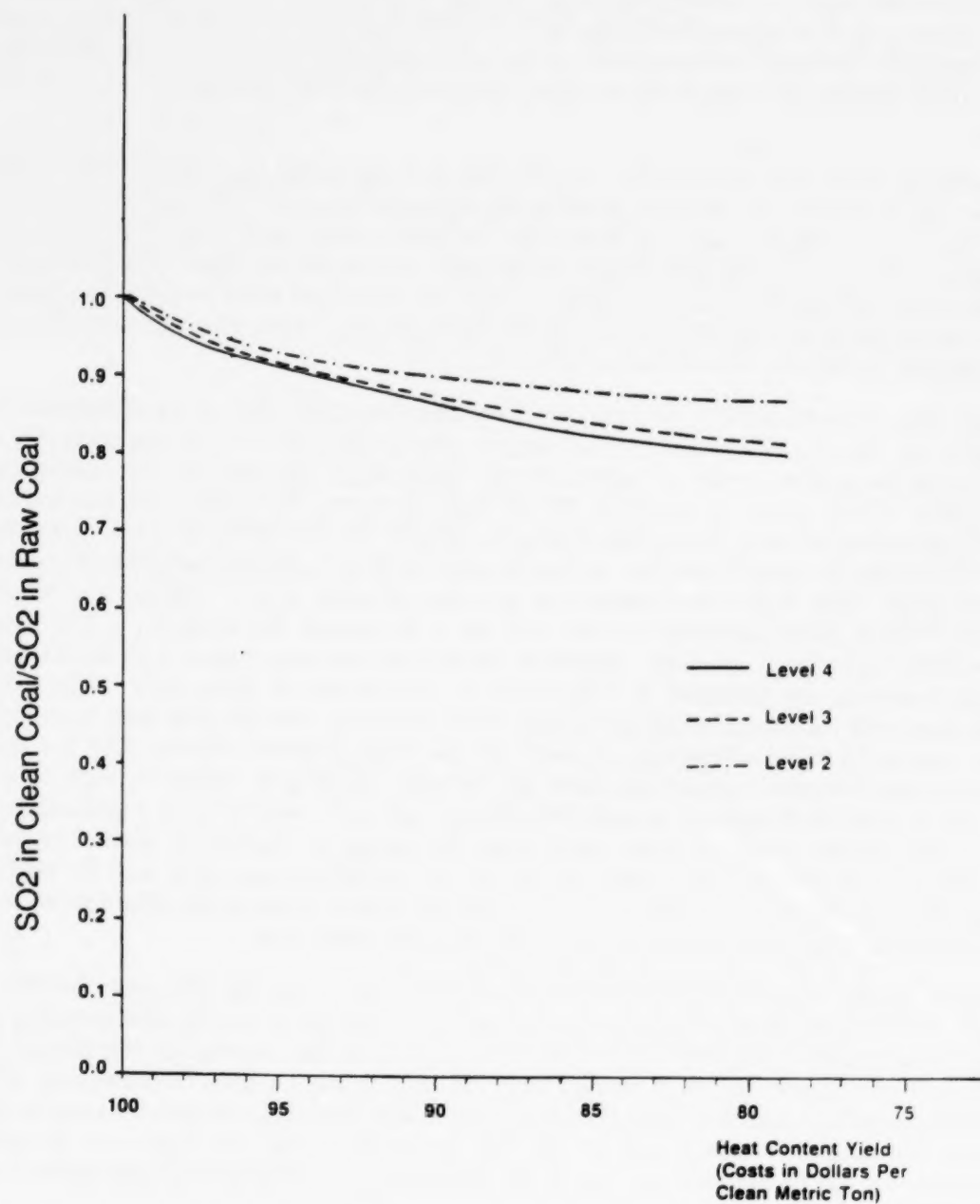


**Table 4.25. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Alabama's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	90	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	12,700	12,700
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	32	60
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.08	0.15
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.09	0.18
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	233.86	155.98
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.69	0.92

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

As was discussed in Chapter 3, the current SO₂ reduction estimate for Pennsylvania was adjusted so that it could be located at a more reasonable point on the clean coal curves. The adjusted estimate was selected so that it would fall on the level 3 curve, at a Btu yield of 85 percent.

Since even an 85-percent yield is quite low, it was decided that, for the additional preparation options, the yield should be held constant and only the preparation level modified. Thus only one improvement was possible -- an increase in the level from 3 to 4. For this reason Table 4.26 presents SO₂ reduction and cost estimates for heavy additional cleaning only; there is no light additional cleaning option for Pennsylvania.

The results show that relatively little is to be gained, in terms of SO₂ reduction, through more intensive cleaning of Pennsylvania's coal. The 43,000 additional metric tons (47,000 short tons) of SO₂ removable through higher-intensity washing represents only 5 percent of the SO₂ in the clean product currently being produced by the state's plants. Compared with the quantity of SO₂ removable through heavy or even light cleaning of the state's uncleaned product (see Table 4.17), the reduction attainable through heavy additional cleaning appears quite small.

Furthermore, the costs associated with this additional reduction -- \$515.25/metric ton (467.43/short ton) SO₂ -- are more than triple the costs that would be incurred in washing the uncleaned product.

Figure 4.15. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Pennsylvania's Clean Production

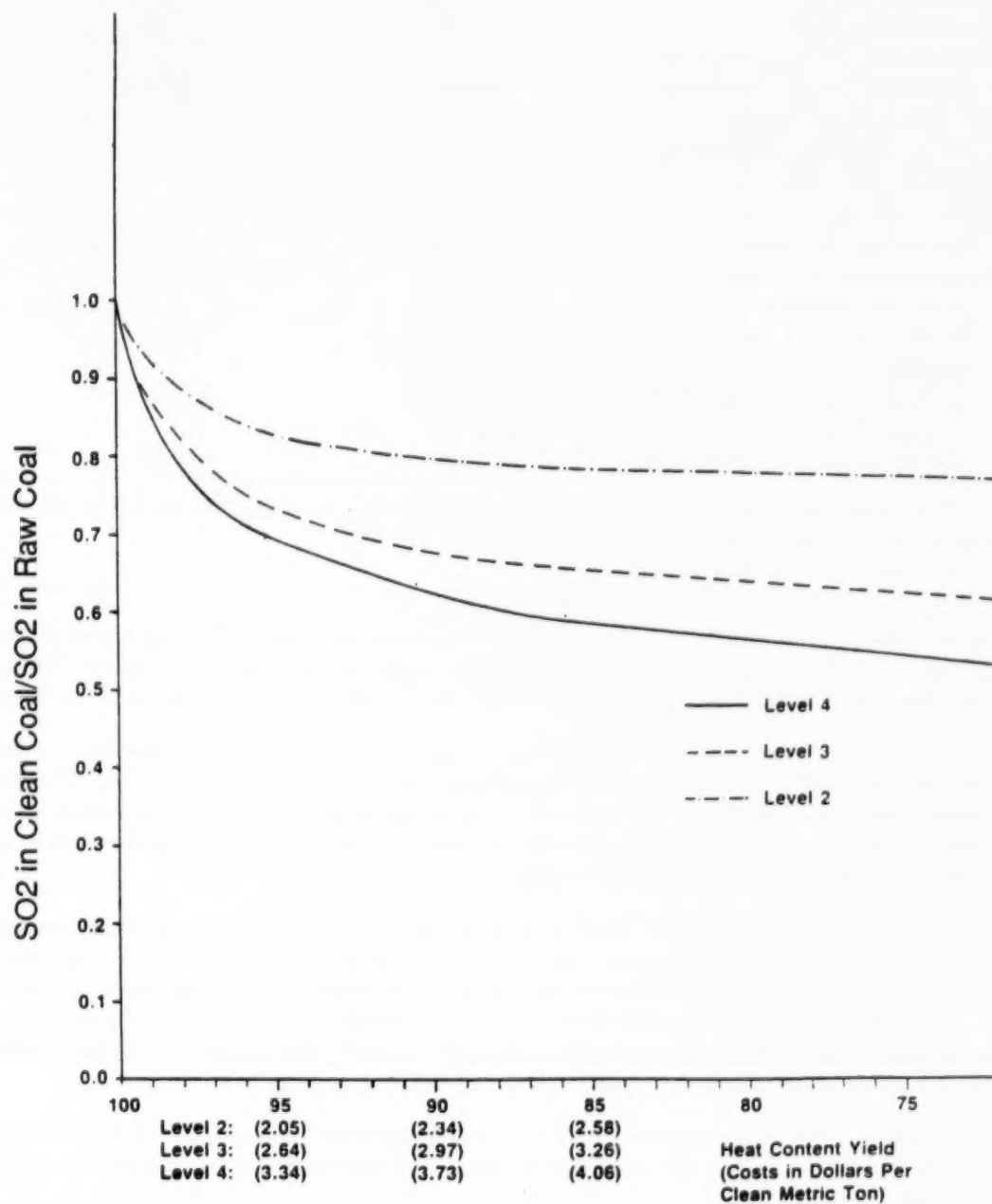


**Table 4.26. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Pennsylvania's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	--	4
Btu Yield (Percent)	--	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	--	41,700
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	--	43
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	--	0.02
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	--	0.05
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	--	515.25
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	--	0.67

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Ohio. Figure 4.16 presents the SO₂ reduction and preparation cost estimates for Ohio's clean production. The curves presented in the figure are similar to those for Ohio's uncleaned product (see Figure 4.7). There are some differences -- e.g., the uncleaned coal curves generally follow a somewhat lower path than the clean product curves -- but the differences are not large.

At present, Ohio appears to be relying primarily on level 3 and 4 cleaning. Therefore, to determine the potential for increased SO₂ reduction through more intensive cleaning, at Ohio's production, the state's current SO₂ reduction estimate was located on the level 3 curve. It was found that the current reduction point falls at a Btu yield of 89 percent. A yield of 89 percent, at level 4, was therefore specified for light additional cleaning; heavy additional cleaning was defined as level 4 preparation at an 85 percent yield.

Estimates of the increases in SO₂ reduction attainable through light additional and heavy additional cleaning are presented in Table 4.27, along with estimates of the costs associated with these estimates. The table shows that light additional cleaning would produce little improvement in SO₂ reduction: only 3 percent of the SO₂ in the clean coal could be removed using the light additional option. Heavier cleaning, on the other hand, would yield more substantial benefits: 10 percent of the SO₂ in the clean coal -- 140,000 metric tons (154,000 short tons) -- could be removed through heavy additional washing. This quantity is almost equal to the amount of SO₂ removable through heavy cleaning of Ohio's uncleaned production (see Table 4.19).

Figure 4.16. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Ohio's Clean Production

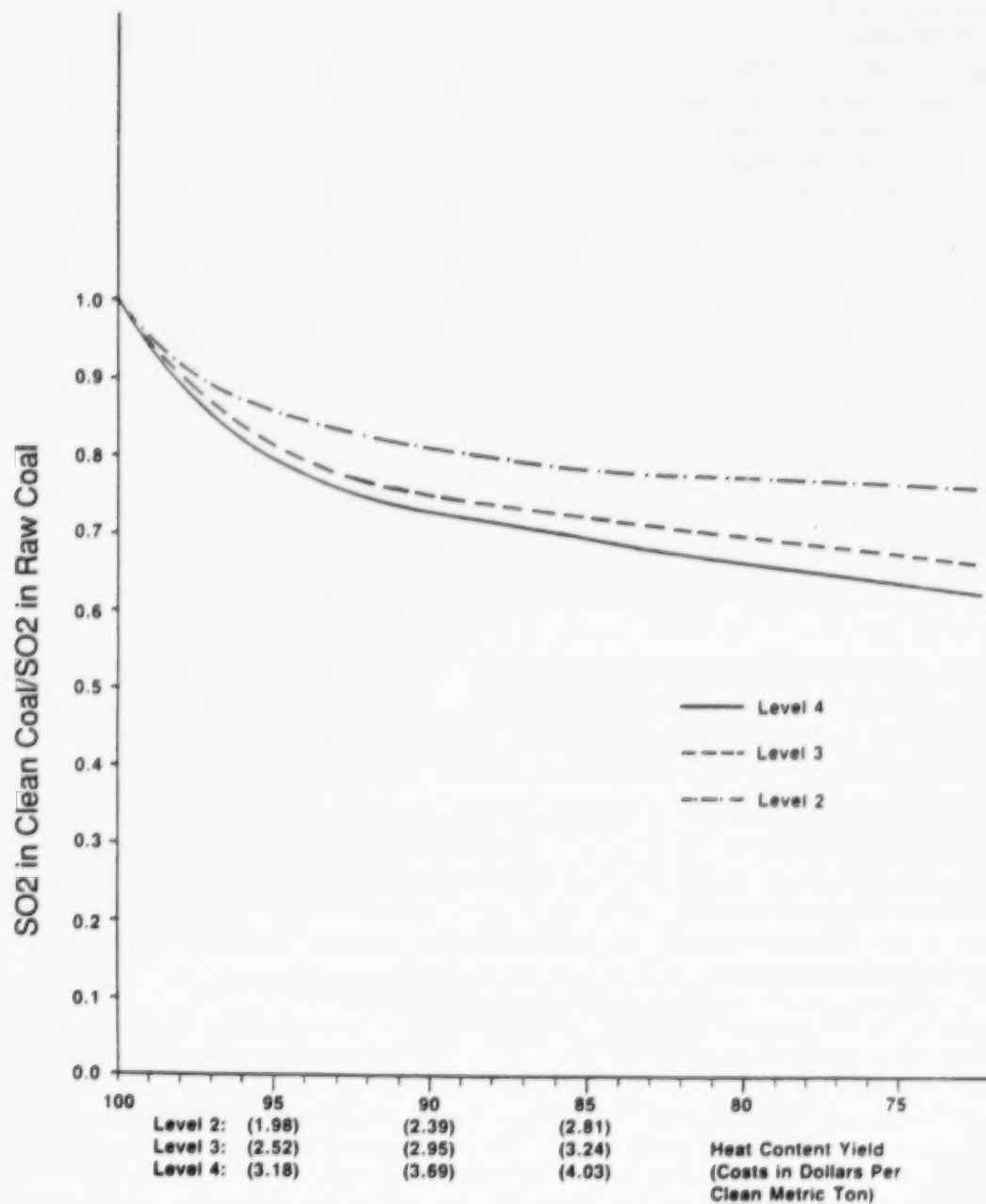


**Table 4.27. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Ohio's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	89	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	27,300	27,300
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	42	140
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.02	0.06
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.03	0.10
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	349.86	130.88
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.64	0.84

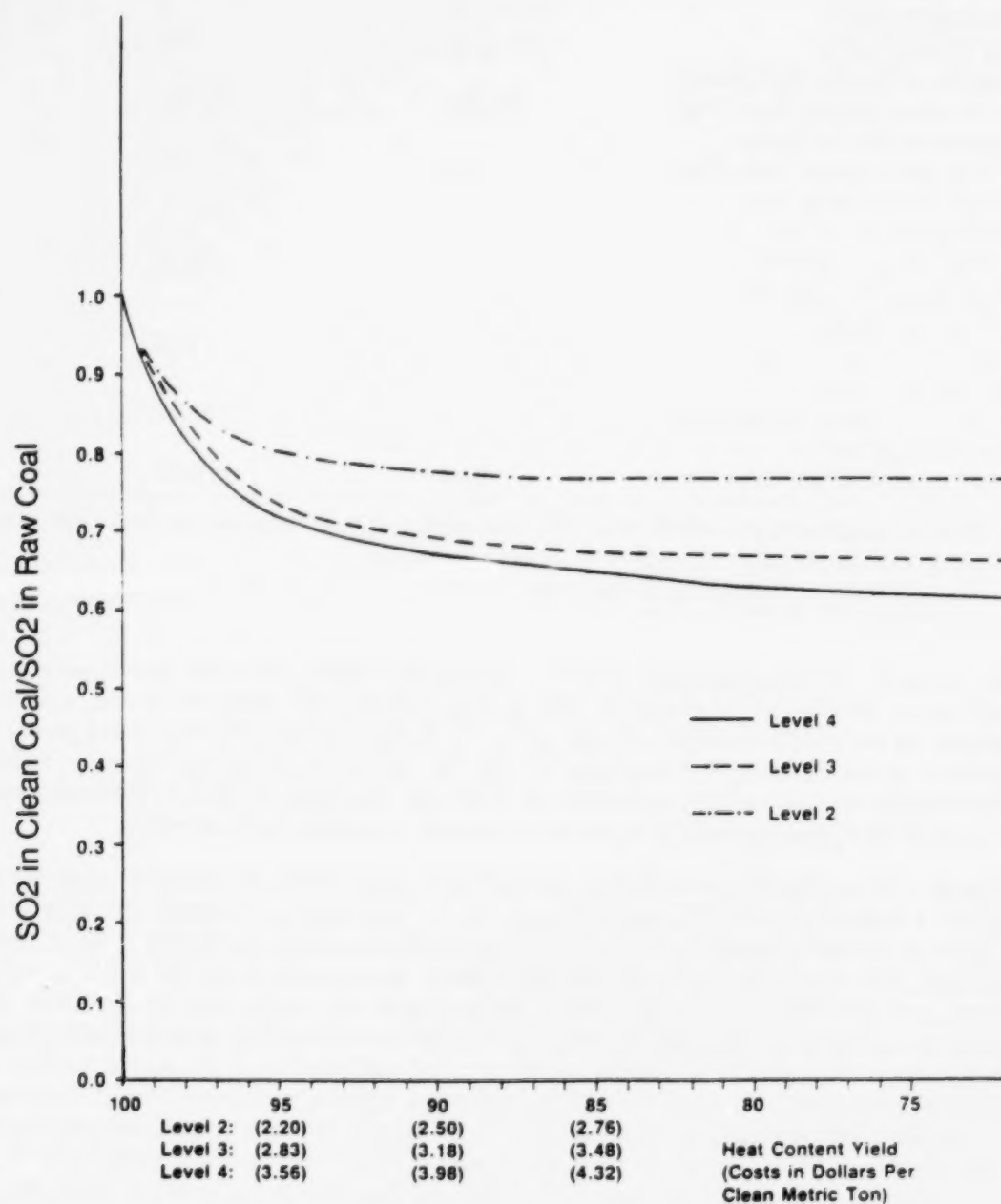
^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Furthermore, the costs associated with heavy additional cleaning are lower than those associated with heavy cleaning of the uncleaned coal, at least in dollars per clean ton of coal. (In terms of dollars per ton of SO₂ removed they are somewhat higher, but the difference is not great.) Thus, whereas in the other states considered thus far the uncleaned production typically contains a substantially larger amount of removable SO₂ than does the clean product, in Ohio the clean and uncleaned coal represent equally important sources of potentially removable SO₂.

Illinois. Comparing Figure 4.17 (SO₂ reduction/Btu yield curves for Illinois's clean coal) with Figure 4.8 (the corresponding curves for the state's uncleaned production) will show that the clean coal is more amenable to washing than the uncleaned product at (at least at yields above 85 percent). The clean coal curves drop to significantly lower points in the 90 to 95-percent yield range, and then follow gentler downward slopes beyond this range, than do the curves for the uncleaned product. The fact that the slopes of the curves are relatively gentle beyond 90 percent suggests that any additional improvements in clean coal quality to be gained through small reductions in the yield at which the coal is washed are likely to be relatively small. Furthermore, although the differentials separating the level 2 and level 3 curves are significant, this is not the case for the level 3 - level 4 curve differentials. Thus, since level 3 preparation is most representative of current cleaning practice in Illinois, increases in the levels at which the plants are operating will yield only small increases in SO₂ reduction.

Figure 4.17. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Illinois' Clean Production



Counterbalancing these negative factors is the fact that, at present, Illinois's plants are typically running at relatively high yields. The state's current reduction estimate falls at a yield of 90 percent on the level 3 curve; thus it may be possible to make fairly substantial reductions in the yields at which the state's plants are operating. A yield of 85 percent was chosen as the heavy additional cleaning yield; for light additional cleaning the yield was held fixed at 90 percent. Level 4 was specified for both additional cleaning options.

The SO₂ reduction and preparation cost estimates for light additional and heavy additional washing of Illinois's clean product are presented in Table 4.28. As can be seen, light additional cleaning would yield only a small increase in SO₂ reduction (4 percent of the SO₂ in the clean coal) at a relatively high cost (\$352.54/metric ton (\$319.82/short ton)) SO₂. Heavy additional cleaning would prove considerably less expensive in terms of dollars per ton SO₂, and yield a fairly significant increase in SO₂ reduction. It is important to note that both the light additional and heavy additional reduction estimates exceed the SO₂ reduction estimate corresponding to heavy cleaning of Illinois's uncleaned coal. In fact, the heavy additional cleaning estimate is more than triple the heavy cleaning estimate for uncleaned coal. This large difference between the two estimates reflects the fact that only a small portion (7 percent) of Illinois's production is not being washed at present; for this reason most of the potential for improving Illinois's SO₂ reduction lies in more intensive cleaning of coal already being washed, rather than in washing currently uncleaned coal. It should be noted that the costs of heavy additional cleaning of the

**Table 4.28. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Illinois' Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	90	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	58,900	58,900
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	88	282
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.02	0.07
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.04	0.12
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	352.54	145.31
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.64	0.90

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

clean coal are competitive with the costs of washing the uncleaned coal, even when measured in dollars per ton SO₂ removed.

Indiana. The SO₂ reduction/Btu yield curves for Indiana's clean production (presented in Figure 4.18) compare unfavorably with the corresponding curves for the state's uncleaned coal. This is especially true in the case of levels 3 and 4; the uncleaned coal curves for these levels follow a significantly lower path than the clean coal curves below the 95-percent yield point.

The current SO₂ reduction estimate for Indiana falls at a yield of 98.5 percent in the level 3 curve. This is very high compared with the estimated yields for other states, and may indicate either that Indiana's current SO₂ reduction has been underestimated, or that its potential SO₂ reduction has been overestimated.

Given the position of Indiana on the SO₂ reduction/Btu yield curve at present, and the possibility that this position is the result of an underestimation of the state's current SO₂ reduction, it was decided that the specifications for light additional cleaning should be relatively conservative. Therefore, light additional cleaning was defined as level 3 cleaning at a 95-percent yield. Heavy additional cleaning was defined as level 4 washing at an 85-percent yield.

Table 4.29 presents the SO₂ reduction and cost estimates for the two preparation options. Not surprisingly, the table indicates that very significant increases in SO₂ reduction can be obtained

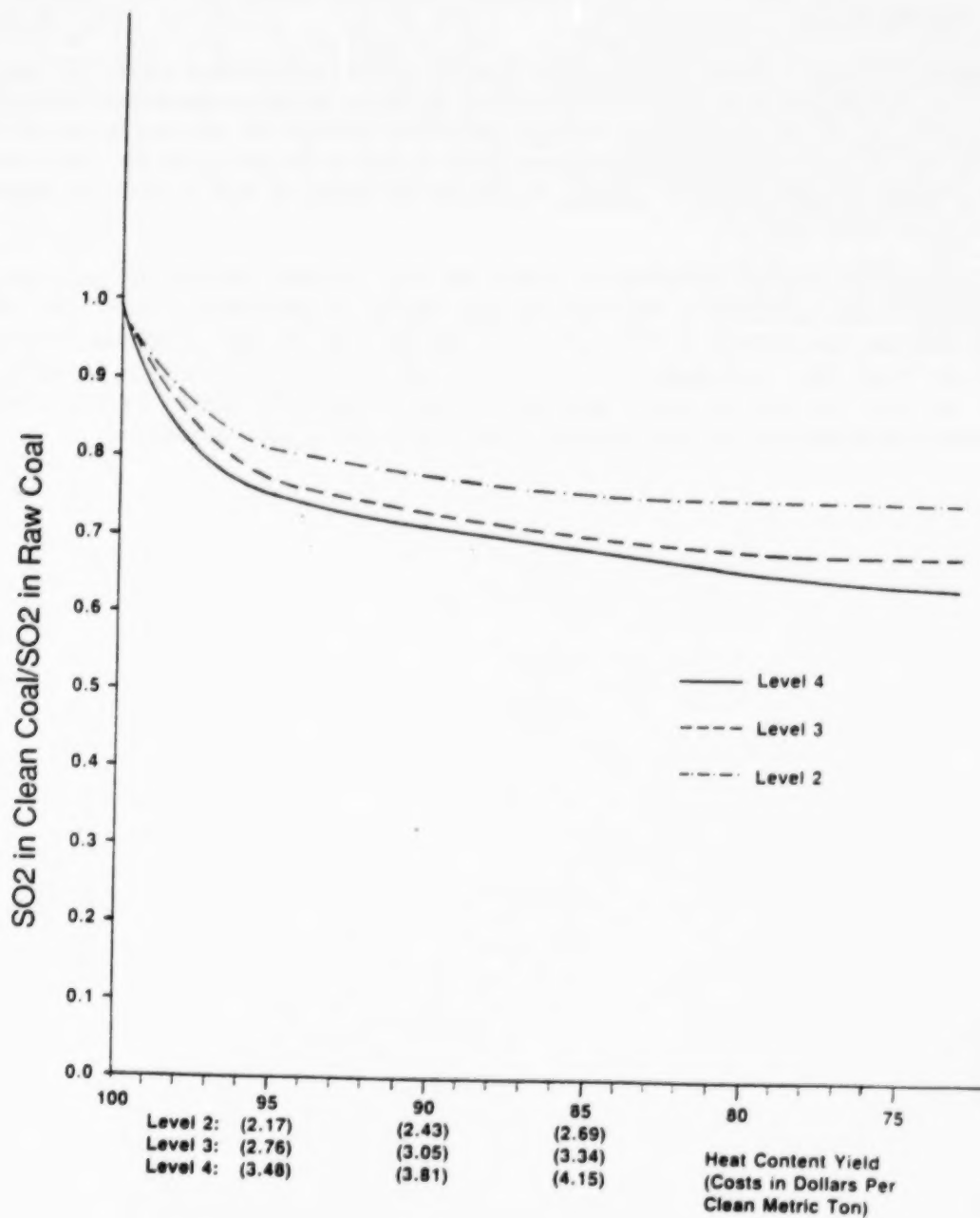
**Table 4.29. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Indiana's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	3	4
Btu Yield (Percent)	95	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	26,200	26,200
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	192	412
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.13	0.28
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.15	0.33
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	57.12	81.09
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.46	1.59

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

Figure 4.18. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for Indiana's Clean Production



through more intensive cleaning of Indiana's coal. In fact, the light additional estimate of 192,000 metric tons (212,000 short tons) is nearly equal to Indiana's current SO₂ reduction tonnage, and the heavy additional reduction is double the current reduction (see Table 4.23). Furthermore, the costs that would be incurred in achieving these results are extremely low, especially when measured on a dollars per ton of SO₂ removed basis. Again, however, these results may point to inaccuracies in either the current SO₂ reduction estimates or the potential SO₂ reduction curves.

Western Kentucky. Figure 4.19 presents the SO₂ reduction/Btu yield curves for western Kentucky's clean production. These curves are very similar to the curves for western Kentucky's uncleaned coal; in fact, there are no notable differences between the two sets of curves. The current SO₂ reduction estimate for the region falls at a yield of 87 percent on the level 3 curve; clearly western Kentucky, unlike Indiana, is already subjecting its coal to relatively intensive cleaning.

The specifications for light additional and heavy additional cleaning, and the SO₂ reduction and cost estimates corresponding to these two cleaning options, are presented in Table 4.30. As the table indicates, the increase in SO₂ reduction attainable through light additional cleaning is relatively small. Heavy additional cleaning would yield more substantial results, at reasonably low costs. However, even the heavy additional reduction estimate falls short of the SO₂ reduction potentially attainable through light cleaning of the region's uncleaned production.

Figure 4.19. Clean Coal SO₂ Content Versus Heat Content Yield and Preparation Costs for West Kentucky's Clean Production

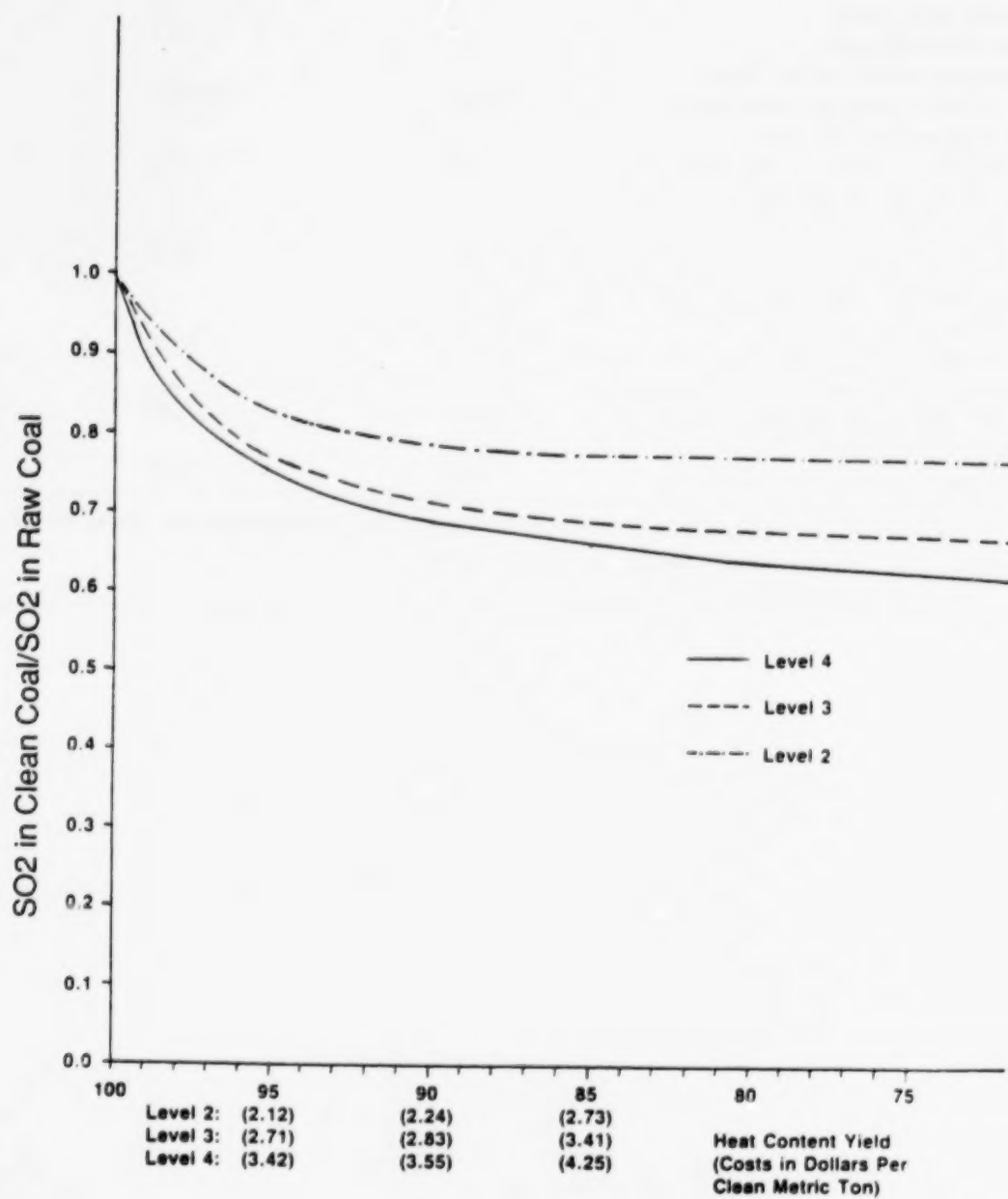


**Table 4.30. SO₂ Reduction and Preparation Cost Estimates
Corresponding to Light and Heavy Additional Cleaning of
Western Kentucky's Clean Production^a**

	Light Cleaning	Heavy Cleaning
Preparation Level	4	4
Btu Yield (Percent)	87	85
Quantity of Coal to Be Cleaned (Thousand Metric Tons/Year)	26,000	26,000
Increase in SO ₂ Reduction (Thousand Metric Tons/Year)	60	104
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Raw)	0.03	0.05
Fractional SO ₂ Reduction (Tons SO ₂ Removed/ Metric Ton SO ₂ Clean)	0.05	0.08
Preparation Costs ^b (\$/Metric Ton SO ₂ Removed)	244.28	159.20
Preparation Costs ^b (\$/Metric Ton SO ₂ Clean Coal)	0.69	0.80

^aThe assumptions upon which these SO₂ reduction and cost estimates are based are discussed earlier in this chapter. See, in particular, Tables 4.4 and 4.5.

^bIncludes both capital and operating costs.

5. Summary of Results

Table 5.1 summarizes the results presented in the two preceding chapters. The "light" potential reduction and cost estimates included in this table were developed by combining the estimates for light cleaning of uncleaned coal with the estimates for light additional cleaning of clean coal; the "heavy" estimates shown in the table represent the combination of the heavy and heavy additional cleaning estimates. The current SO₂ reduction estimates are equivalent to those presented in Chapter 3, except in the cases of Pennsylvania and East Kentucky. As was discussed in Chapter 4, the current estimates for these two areas had to be revised to bring them in line with the potential reduction estimates; the values presented in Table 5.1 are the revised estimates.

The results summarized in Table 5.1 were discussed in detail in the preceding chapters; however, at this point a few general comments are in order. First, when the current reduction estimates are compared with the potential estimates, it becomes evident that the potential for significantly increasing SO₂ reduction through greater utilization of physical coal cleaning is high. This observation holds true for almost every major coal-producing state in the east; however, the degree to which current SO₂ reduction can be increased varies widely from state to state.

Second, within each state the potential SO₂ reduction estimates, and the costs associated with these estimates, vary widely depending on the specified preparation level and Btu yield. In this study, state level potential reduction and cost estimates were developed for two preparation scenarios or options; the specifications for the two options were developed with the goal of representing, to the degree possible, the full range of options actually available. Given the wide variation in the reduction and cost estimates with operating conditions, it is very important to recognize that the two specified options are but two points chosen, somewhat arbitrarily, from a continuum of available options.

Table 5.1. Current and Potential SO₂ Reduction Estimates, and Preparation Cost Estimates

Region and State	Total 1983 Raw Production (Thousand Raw Metric Tons)	Total SO ₂ ^a in Raw Coal (Thousand Raw Metric Tons)	Quantity of SO ₂ (Thousand Metric Tons)			Preparation Costs (\$/ Ton SO ₂ Removal)	
			Currently ^b	Potentially		Light	Heavy
				Light ^c	Heavy ^c		
Appalachia							
Alabama	26,300	766	55	80	182	309.06	180.47
E. Kentucky	50,700	1,209	159	145	240	306.17	238.84
Ohio	33,400	2,594	741	126	282	204.84	119.66
Pennsylvania	64,400	2,845	827	312	486	167.03	172.58
Virginia	25,000	386	45	16	21	464.91	455.13
W. Virginia	121,000	4,066	943	286	519	309.17	194.53
Total	320,800	11,866	2,770	965	1,730	251.71	183.99
Midwest							
Illinois	63,000	4,134	1,463	142	367	277.59	141.61
Indiana	33,700	1,986	204	322	610	74.48	84.76
W. Kentucky	36,500	2,967	848	229	385	151.23	114.96
Total	133,200	9,087	2,515	693	1,362	141.46	108.79
Grand Total	454,000	20,953	5,285	1,658	3,092	205.63	150.79

^aQuantity includes cleaned and uncleaned.

^bTennessee, Colorado, Missouri, New Mexico, Maryland, and Utah costs are not included here, because potential SO₂ reduction estimates were not developed for these states (see Table ES-5, especially footnote a).

^cThe definitions of light and heavy cleaning vary by region, and are presented in Table ES-5.

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Appendix A. Critique of the Skea And Rubin Regression Analysis

As was noted in Chapter 4, the regression analysis performed by Skea and Rubin is problematic. This appendix explains these problems in greater detail. The form of the regression equation used to predict plant Btu yields for given levels of sulfur reduction is:

$$\log(1 - Y') = a + b \log \left(\frac{S'}{P - S'} \right) + c \log (SR') \\ + d \log (AR') + e \log (HR')$$

where

Y'	=	Btu yield of washing
a, b, c, d, e	=	constants
S'	=	fractional reduction in S' through washing
P	=	fractional of all sulfur that is pyritic
SR'	=	pounds of SO ₂ per million Btu in the raw coal
AR'	=	pounds of ash per million Btu in the raw coal
HR'	=	pounds of ash-free coal per million Btu in the raw coal.

The regression results indicate that, for many regions, raw coal quality characteristics (SR', AR', and HR') are significantly correlated with Btu yield (Y'). The model documentation suggests that this result stems from a correlation between raw coal quality characteristics and washability characteristics. The documentation contains the following statement: "It is observed that, within particular geographical regions, the properties of the original seam-quality coals are significantly correlated with their washabilities." The basis for this observation is the regression results. However, while the regression results do in fact indicate a correlation between raw coal quality and Btu yield, this does not necessarily suggest a correlation between raw coal quality and washability characteristics. In other words, although the regression results indicate a correlation between Q, the raw coal quality characteristics, and Y', and it is clear that Y is in fact a function of W, the washability characteristics, it does not necessarily follow that Q and W are correlated. As an analogy, one might find that a correlation exists between the incidence of lung cancer and geographic location, and that another correlation exists between lung cancer and smoking; this does not necessarily indicate a relationship between smoking and geographic location. The review of the Skea and Rubin regression analysis conducted for this study suggests that the observed correlation between Q and Y' may arise from factors other than the hypothesized correlation between Q and W, including the techniques employed in the statistical analysis.

Tables A-1, A-2, and A-3 present the results of the regression analysis. Each table represents a different preparation level; Table A-1 corresponds to level 2 preparation, Table A-2 to level 3 washing, and Table A-3 to level 4. For each level, the preparation model was run for each coal

Table A-1. Coefficients^d for Equation A-1: Level 2 Process Yields

Region	a	b	c	d	e	R-Sq. (%) ^a	N ^b
1	-40.958	0.81860 (18.34)	NS ^c	0.22289 (2.65)	9.060 (5.43)	44.2	508
2	-3.3826 (12.99)	0.73402	NS ^c (3.48)	0.32657	NS ^c	37.1	306
3	-2.8682	0.81500 (10.30)	0.7000 (5.00)	NS ^c	NS ^c	49.4	116
4	-43.68	1.0092 (10.00)	-0.5290 (2.28)	0.4421 (2.29)	9.814 (2.51)	41.8	154
5	-3.5992	1.2147 (6.41)	-1.2668 (2.72)	0.8145 (4.10)	NS ^c	66.0	36
6	-3.5681	0.99243 (25.84)	NS ^c	0.5647 (7.83)	NS ^c	50.4	706
7	-71.54	1.0909 (7.89)	0.5938 (3.45)	NS ^c	16.200 (3.66)	54.5	76
8	-62.556	0.99369 (19.35)	NS ^c	NS ^c	14.111 (6.52)	68.2	188
9	-135.48	1.0155 (4.99)	NS ^c	1.5298 (5.35)	31.118 (4.60)	76.5	22
10	-2.89757	0.87995 (12.66)	NS ^c	NS ^c	NS ^c	47.4	180
11	-2.7948	1.0495 (10.30)	0.9014 (5.84)	-0.5706 (2.08)	NS ^c	59.6	100
12	-44.65	0.8793	NS ^c	0.8122	9.334	77.8	95
13	23.41	1.2118 (6.13)	1.3763 (2.03)	1.3568 (4.21)	-6.889 (5.16)	83.7	22
14	48.895	0.91675 (10.37)	NS ^c	0.5649 (3.65)	-12.405 (7.75)	53.3	118
15	-3.7511	0.7381 (2.09)	NS ^c	NS ^c	NS ^c	19.5	20
16	-81.68	1.4318 (5.52)	-1.8254 (5.00)	NS ^c	18.788 (3.88)	79.1	22
17	-5.238	1.1810 (5.23)	-3.606 (3.28)	1.3020 (3.10)	NS ^c	67.7	21
18	102.05	1.01044 (10.99)	0.8720 (2.60)	1.9635 (2.56)	-25.286 (6.49)	72.5	63

^aR-sq = R-squared.

^bN = Sample size.

^cNS = Coefficient not significant at the 95 percent level.

^dt-statistics are in parentheses.

Note: t-statistics are in parentheses.

Table A-2. Coefficients^d for Equation A-1: Level 3 Process Yields

Region	a	b	c	d	e	R-Sq. (%) ^a	N ^b
1	-55.543	0.92621 (43.57)	0.12014 (2.82)	0.15231 (2.83)	12.016 (10.78)	66.4	1063
2	-3.4735	0.88423 22.88	NS ^c	0.40630 5.46	NS ^c	53.8	474
3	-33.61	0.85743 (20.04)	0.54708 (5.78)	a	7.317 (2.82)	64.4	253
4	-58.45	1.06502 (17.10)	NS ^c	NS ^c	13.342 (5.34)	56.6	240
5	-60.20	1.0145 (9.39)	-1.3890 (4.24)	0.7656 (5.72)	13.408 (2.33)	74.2	55
6	-26.03	0.9990 (40.59)	a	0.60847 (9.37)	5.261 (4.26)	61.4	1128
7	-50.31	1.07858 (11.25)	0.5614 (3.87)	NS ^c	11.151 (3.15)	62.0	107
8	-68.676	0.99091 (29.34)	NS ^c	NS ^c	15.523 (9.20)	76.7	279
9	-89.20	0.9246 (32.15)	0.4685 (2.67)	1.4982 (4.16)	19.937 (6.81)	81.8	37
10	-2.5012	0.98812 (22.64)	-0.2261 (2.11)	NS ^c	NS ^c	65.6	274
11	-4.2308	0.99291 (14.73)	0.8589 (7.82)	NS ^c	NS ^c	67.6	144
12	-29.547	0.91021 (21.53)	NS ^c	1.0232 (6.99)	5.659 (2.49)	81.9	143
13	23.05	1.1562 (8.40)	1.5190 (5.67)	1.9837 (6.61)	-7.296 (2.50)	82.9	40
14	37.476	1.02366 (17.46)	0.4489 (2.49)	0.4887 (3.93)	-9.878 (5.46)	68.4	172
15	-3.6614	1.0037 (4.25)	NS ^c	NS ^c	NS ^c	42.0	27
16	-75.30	1.2654 (7.14)	-1.9103 (6.12)	NS ^c	17.241 (4.49)	75.0	37
17	-6.0601	1.0878 (6.13)	-3.2300 (3.27)	1.4965 (3.91)	NS ^c	68.8	26
18	86.08	0.85460 (14.51)	0.7122 (2.64)	1.7416 (2.78)	-21.578 (6.08)	74.9	91

^aR-sq = R-squared.

^bN = Sample size.

^cNS = Coefficient not significant at the 95 percent level.

^dt-statistics are in parentheses.

Note: t-statistics are in parentheses.

Table A-3. Coefficients^d for Equation A-1: Level 4 Process Yields

Region	a	b	c	d	e	R-Sq. (%) ^a	N ^b
1	-59.424	0.82754 (53.78)	0.15043 (3.95)	0.10571 (2.18)	13.3875 (13.57)	70.5	1365
2	-18.473	0.89523 (28.20)	NS ^c	0.40916 (5.77)	3.545 (2.25)	60.8	549
3	-37.284	0.81268 (26.71)	0.44684 (0.532)	NS ^c	8.198 (3.70)	68.8	345
4	-83.27	1.04005 (20.98)	-0.3281 (2.02)	NS ^c	19.341 (7.08)	62.5	284
5	-4.3524	0.95280 (10.83)	-1.0107 (3.15)	0.8315 (6.26)	NS ^c	73.8	63
6	-31.860	1.01639 (49.85)	NS ^c	0.63986 (10.75)	6.592 (5.79)	67.6	1325
7	-42.88	1.05105 (14.08)	0.6032 (4.63)	NS ^c	9.364 (2.98)	68.1	124
8	-71.285	0.99877 (35.11)	NS ^c	NS ^c	16.129 (10.44)	80.4	321
9	-110.68	0.9716 (8.79)	NS ^c	1.6752 (7.41)	25.074 (4.55)	78.5	45
10	-2.5135	0.96872 (25.66)	-0.2614 (2.59)	NS ^c	NS ^c	68.7	305
11	-4.2720	0.96080 (17.20)	0.8418 (8.40)	NS ^c	NS ^c	70.2	158
12	-25.863	0.85047 (24.21)	NS ^c	1.0916 (8.69)	4.733 (2.39)	84.3	155
13	15.55	1.13196 (12.03)	1.5520 (6.83)	2.1527 (7.65)	-5.663 (2.30)	82.9	57
14	36.975	1.05135 (22.12)	0.4091 (2.56)	0.5022 (4.48)	-9.751 (5.87)	74.3	204
15	-3.7192	1.0631 (5.77)	NS ^c	NS ^c	NS ^c	53.4	31
16	-80.38	1.1620 (9.12)	-1.7362 (6.88)	NS ^c	18.352 (6.05)	80.2	43
17	-6.9450	0.9900 (7.40)	-3.2827 (4.07)	1.7650 (5.24)	NS ^c	77.4	28
18	83.96	0.73650 (13.33)	0.6404 (2.47)	2.0169 (3.33)	-21.242 (6.13)	71.9	94

^aR-sq = R-squared.

^bN = Sample size.

^cNS = Coefficient not significant at the 95 percent level.

^dt-statistics are in parentheses.

Note: t-statistics are in parentheses.

contained in the U.S. DOE washability data base. Each coal was washed in 5 percent sulfur (S' , = 5 percent, 10 percent, 15 percent, etc.) up to the maximum level of sulfur reduction, as determined by the pyritic sulfur content of the coal and the washing capabilities of each preparation level. The results were pooled for each washability region; the definitions of washability regions, along with the number of DOE washability samples available in each region, are presented in Table A-4. The results were then used as the regression analysis data base.

This methodology results in two primary problems in interpretation:

- The sample sizes are artificially high because they are based on the output of the coal cleaning model rather than the observed washability data. As a result, the t-statistics are also artificially high, and it is not possible to determine which variables are actually significant.
- There is a potentially serious problem of autocorrelation arising from the pooling of data for multiple sulfur reduction levels at each sample point. No results are presented to indicate that this potential problem was examined.

In addition, the model documentation fails to provide the standard error of the estimate for each regression equation. Without the overall standard error of the estimate, it is not possible to judge how much variation remains in the estimated results.

The two problems noted above are discussed separately below.

Sample Sizes

The sample sizes shown in Tables A-1 through A-3 are almost always larger, and often much larger, than the number of DOE samples given in Table A-4. If the sample sizes represented actual observations from the washability data, then the sample sizes would not be nearly so problematic. For example, if each line in a washability table were used to generate one observation for the regression analysis, then the primary question to ask would be whether the "design effect" inherent in this cluster sample reduced the effective sample size. This problem is treated in standard texts on sampling. (See, for example, Leslie Kish, *Survey Sampling*.)¹⁰

However, the problem appears to be somewhat greater than a simple correction for the cluster sampling inherent in the DOE samples. The sample sizes in these tables appear to have been generated from the output of the cleaning model at increments of 5-percent sulfur reduction up to the maximum level of reduction implied by the washability data. It is not clear how the figure of 5 percent was chosen, but it appears that the methodology is consistent with an arbitrary increment. In this case, the sample size could have been approximately doubled merely by reducing the increment to 2.5 percent. The sample size has a direct bearing on the standard errors, approximately equivalent to reducing the standard error by the square root of the ratio of the increased sample size to the original. For example, quadrupling the sample size will result in standard errors only half as large, other things being equal. Since the sample sizes in the tables can be significantly larger than the number of original samples, the values of the t-statistics may be arbitrarily inflated, and many of the variables classified as significant may appear significant only because of these arbitrarily high sample sizes.

Table A-4. Washability Regions

Washability Region	Region	AUSM Region Name	Number of DOE Samples
1	1	E. Pennsylvania	143
2	2	W. Pennsylvania	62
3	3, 4	N.E. West Virginia/Maryland	39
4	5, 6	N.W. West Virginia/West Virginia Panhandle	32
5	7, 8, 10, 11	S.E./S.W. West Virginia/Virginia	24
6	9	Ohio	148
7	12, 14	E. Kentucky/N. Tennessee	25
8	13	W. Kentucky	37
9	15, 19	S. Tennessee/Alabama	11
10	16	Illinois	40
11	17	Indiana	21
12	18	Iowa	17
13	20, 21	E. Oklahoma/Arkansas	15
14	22, 23, 24, 25	W. Oklahoma/Kansas/Missouri/Texas	30
15	26, 31	N. Colorado/Wyoming	12
16	27, 28, 32	S. Colorado/N.E. New Mexico/Utah	28
17	29, 30	W. New Mexico/Arizona	15
18	33, 34, 35	N. Dakota/Montana/Washington	11
<i>Total</i>			710

In any case, it is important to examine the relationship between the within-sample variation in yield values and the across-sample variation in yield. If most of the variation is across samples, then it may be largely correct to assume, as implied by the analysis, that the results can be applied to new samples not included in the observations. On the other hand, if most of the variation is within samples, the increase in sample size that results from pooling multiple observations on each DOE sample may be largely illusory and limit the confidence with which the results may be extended.

Problems of Autocorrelation

Whenever data are pooled as they were in the regressions performed to estimate yields, the question of autocorrelation in the error term arises. The reason why this question is more than a statistician's formal quibble is that autocorrelation can result in coefficients that are biased.

Autocorrelation arises when the error terms in the regression results are correlated with each other, contrary to the assumptions of Ordinary Least Squares (OLS) regression. For example, if the regression estimates of yield are higher than the model's estimates for all the observations derived from a single DOE sample, the error terms will be correlated. This correlation can have the effect of falsely contributing to the statistical significance of independent variables; when a

correction is made for autocorrelation, previously significant variables may no longer be significant.

The standard test for autocorrelation is the Durbin-Watson statistic. The model documentation does not provide values of the Durbin-Watson statistic for the regression results.

Both of the above problems arise because the data are pooled. In pooling the data, for example, it is implicitly assumed that it is correct to estimate a single coefficient of SR' for all levels of sulfur reduction. It is not clear whether this is a valid assumption; the impact of the raw sulfur level may not be the same at low levels of sulfur reduction as it is at high levels of sulfur reduction.

Another possible problem might arise from the fact that S represents a relative, as opposed to absolute, measure of the change in sulfur content. If yield in fact depends on the absolute change in sulfur content, then SR' may be significant merely because when combined in an equation with the relative change in sulfur, it helps define the absolute change. This point is worth considering because it is the raw values of sulfur and ash that purport to provide the connection between the washability data base and the reserve data.

To summarize, there may exist reasons other than the proposed correlation between raw coal quality and washability that explain the significance of the coefficients of SR' , AR' , and HR' . For example, the significance of these coefficients may be due to the artificially high sample sizes or the fact that the absolute change in sulfur depends on both the raw sulfur content (SR') and the relative change in sulfur (S). Furthermore, not only do other explanations exist for the significance of these variables, but the model documentation presents no theoretical basis justifying the proposed correlation between raw quality and washability. Without some geological hypothesis supporting the claimed correlation, the other possible explanations take on additional weight. The lack of geological hypothesis in the model documentation would not be so problematic if the empirical data indicated a strong, uniform relationship between quality, and washability. In fact, however, not only are the coefficients of the quality variables often insignificant but the sign of the significant coefficients often changes across regions (see Tables A-1 through A-3).

It should be noted the same problems apply to the regression equation used to predict ash content; this discussion has focused on the yield equation because it is clearly of critical importance.

Appendix B.

Uncertainty Analysis

As was discussed in Chapter 1, some major data problems were encountered during the course of this study. Since these problems undoubtedly had an effect on the accuracy of the results, an attempt was made to determine the range of uncertainty surrounding the state-level current and potential SO₂ reduction estimates presented in Chapter 5. The results of this uncertainty analysis are presented in this appendix. However, at the outset it must be stated the uncertainty analysis was plagued by the same data problems that hampered the entire study. In order to develop completely objective estimates of the range of uncertainty surrounding the SO₂ reduction estimates, it would be necessary to obtain at least a small amount of the data that was lacking. However, as was noted in Chapter 1, obtaining these data would require a considerable amount of effort; e.g., in the case of washability data, it would be necessary to collect at least one coal sample from at least one bed/county combination,* and perform washability tests on the sample. Therefore, a different approach, involving a certain amount of subjective judgement, was employed. Although the uncertainty ranges derived through the application of this approach must themselves be viewed as uncertain, they provide at least a rough indication of the potential range surrounding the current and potential SO₂ reduction estimates. Furthermore, it is hoped that the detailed identification, description and analysis of the numerous specific data problems, developed as a part of the uncertainty analysis, will provide the reader with a better qualitative understanding of the nature of the problems encountered and their potential impact on the results.

Methodology

To estimate the error associated with the analytical results, the total error was decomposed into a set of distinct error measurements where each error measurement represents the uncertainty associated with critical steps in the analytical procedure. Thus, the extension of a raw sulfur content measurement from a single point to a large area individually contributes a measure of uncertainty to the results, while the use of bed/county averages to approximate the sulfur content of the raw coal feed to the preparation plant contributes another measure of uncertainty. The contribution of each uncertainty measure to the total error is not simply additive since small errors in critical steps may have a larger impact on total error than large errors in other steps. Consequently, if error estimates are assigned to each step in the analysis, the problem reduces to combining the individual error estimates meaningfully so that the set of error estimates in combination represents a reasonable estimate of the total error associated with the analysis.

A procedure was developed whereby the individual uncertainties could be combined meaningfully to provide an overall assessment of uncertainty. The procedure consisted of 1)

* If a reasonably accurate (as opposed to simply objective) estimate of the uncertainty is desired, then it would be necessary to sample more bed/county combinations; furthermore, the number of samples obtained from each combination would have to be considerably larger than one.

decomposing total uncertainty into a distinct set of components that contribute individually to the total error in the analysis and 2) establishing a set of weights which quantify the contribution of each component's error to the total uncertainty. Each component influences the overall uncertainty uniquely, with some having more effect on total error than others. For instance, the error associated with extending point values of raw sulfur content to a large area may be perceived as affecting total uncertainty more than, say, the inclusion of core and channel samples. The degree to which each error component influences total error was quantified as the relative weight of the error component in the total error.

The method used to establish relative weight for each component used pairwise comparisons between each component to determine a matrix of comparisons where each element of the matrix reflects a qualitative assessment of how more strongly one component contributes to overall uncertainty than the other. Mathematical transformation of the matrix yielded a consistent set of weights. The method uses pairwise comparison between error components to rank systematically each component according to importance and to assign meaningful numerical weights to the ranking. (The method is described in detail in T.L. Saaty, *The Analytical Hierarchy Process*.¹¹) The pairwise comparisons are obtained subjectively based on a thorough understanding of each error component and the extent to which each is relevant to the overall uncertainty. The comparisons are taken qualitatively and corresponding scale values are assigned. The comparisons indicate the relative importance of one error component over another in contributing to the total error. The assignment of scale values is based on a determination of which of two error components are more important and a perception of the magnitude of importance, expressed as a number on a given scale. These numerical scale values are shown in Table B-1, which presents integer assignments to the scale of values of the components. Each value assigned to the pairwise comparisons may be regarded as an estimate of the ratio of the two components being compared, taken to the nearest integer.

Table B-1. The Scale and Its Description (Saaty, 1980)

Intensity of Importance	Definition	Explanation
1	equal importance	two factors contribute equally to overall uncertainty
3	weak importance of one over another	experience and judgment slightly favor one factor over another
5	essential or strong importance	experience and judgment strongly favor one factor over another
7	demonstrated importance	a factor is strongly favored and its dominance is demonstrated in practice
9	absolute importance	the evidence favoring one factor over another is of the highest possible order of affirmation
2, 4, 6, 8	intermediate values between judgments	when compromise is needed

The procedure for deriving weights consists of the construction of a matrix of pairwise comparisons where each element of the matrix corresponds to the scale value assigned to the comparison. The method reduces to obtaining the characteristic sector of the matrix. The characteristic sector determines the weights assigned to each error component.

Current SO₂ Reduction Estimates

As was discussed in Chapter 1, the primary data problem encountered during the development of the current SO₂ reduction estimates was the lack of data on the sulfur content of the raw feed to existing preparation plants. As a result of this problem it was necessary to estimate the average raw coal sulfur content for each bed/county combination, and then use the bed/county averages to approximate the sulfur content of the raw feed. There are a number of problems with this procedure, each of which contributed to the overall uncertainty associated with the estimates of current SO₂ reduction. In order to develop estimates of the range of uncertainty surrounding the current SO₂ reduction estimates, the major problems associated with the raw sulfur content estimation procedure were identified, the uncertainty range associated with each problem was estimated, and the problems were assigned relative weights according to the procedure described above.

In the following subsections, the problems or potential error sources considered in the uncertainty analysis are each discussed in turn. But before turning to the individual problems, one general point needs to be discussed. Due to the relative size of the terms in the equation used to estimate the quantity of sulfur removed by each cleaning plant (see the first equation in Chapter 3), any errors in the estimates of the raw feed sulfur content were significantly magnified in the final SO₂ reduction estimates. Specifically, the second term of this equation, which represents the quantity of sulfur in the clean product, usually was fairly large relative to the problematic first term (representative of the raw feed sulfur content). Hence, when measured as a percent of the true value, an error in the first term was magnified in the result. The sensitivity of the current SO₂ reduction estimates to errors in the raw feed sulfur content was taken into account in estimating the uncertainty ranges associated with the problems discussed below, and will help to explain why these ranges may seem unduly wide.

1.

Inclusion of Quality Analyses for Face and Channel Samples in the EIA/USBM Analytical File

The EIA/USBM analytical file used to estimate the average raw sulfur content for each bed/county combination includes, in addition to analyses that represent the quality of the run-of-mine product, analyses that are more representative of the in-seam quality of the coal (i.e., analyses of face and channel samples). Since the in-seam quality of coal can differ from its as-mined quality, due to the mixing of the coal with rock from the surrounding strata during mining, the inclusion of in-seam analyses in the bed/county averages used to approximate the raw feed's sulfur content represents a potential source of error. However, although the differences between a coal's in-seam and as-mined quality can be substantial, the number of face and channel sample analyses included in the EIA/USBM analytical file is very small relative to the number of

analyses performed on samples taken from the run-of-mine product. Hence, the inclusion of face and channel samples in the analytical file was judged to be a relatively insignificant problem.

2.

***Extension of Raw Sulfur Content
Measurements from Single Point to
All the Coal Contained in the
Point's Area of Influence***

Each analysis in the EIA/USBM analytical file represents the quality of coal at a specific point (the point at which the sample was taken) within a bed and county. In developing the bed/county raw sulfur content averages, the analyses are implicitly assumed to represent not only the coal quality at the sampling point, but also the quality of all the coal contained in an (unknown) area of influence surrounding the point. Since the quality of coal can vary substantially even within the same bed and county, the extension of quality data from the sampling point to all the coal contained in the point's area of influence represents a potential source of errors. This problem was judged to be one of the most significant of those contributing to the uncertainty of the current SO₂ reduction estimates, since, potentially, it effects every bed/county combination.

3.

***Assumption that Areas of
Influence are Equal
(and Seam Thickness Is Constant)
Within Each Bed/County Combination***

As was discussed in Chapter 3, the procedure used to estimate the average bed/county raw sulfur contents is based on the implicit assumption that the areas of influence surrounding each sampling point are equal within a given bed/county combination. At this point it might be added that the procedure also assumes (again implicitly) that the seam thickness is the same in each of the equal areas of influence. These assumptions, although not as significant as the assumption that the quality data can be extended from the sampling point throughout the area of influence in the first place, are nonetheless a significant source of uncertainty.

4.

***Use of Bed/County Averages as
Approximations to the
Sulfur Content of the Raw Feed***

Each of the three problem discussed above reduced the accuracy of the estimates of the average raw sulfur content for each bed/county combination; in this way they contributed to the uncertainty associated with the current SO₂ reduction estimates. However, even if these problems did not exist, and the estimated average sulfur content were exactly equal to the true average sulfur content for each bed/county combination, there would still remain a potential for error. As discussed in Chapter 1, the use of bed/county averages as approximations to the sulfur content of the raw feed to plants is itself problematic. The sulfur content of the coal being mined at present

is not necessarily equal to the overall average sulfur content of all the reserves contained in each bed/county combination; in fact, as was noted in the above-cited section, there is good reason to believe that the sulfur content of the coal being mined at present is lower than the average sulfur content of the reserves in the ground. Hence, the use of bed/county averages as estimates of the sulfur content of the raw feed was not only judged to be a significant source of errors relative to the other identified problem (since, like problem number 2, its potential effects were all pervasive); even more importantly, it was judged to introduce biases (towards the high side) in the current SO₂ reduction estimates.

5.

*Exclusion of Small Mines
Served By Cleaning Plants*

Even if it could be assumed that accurate bed/county sulfur content averages were obtained, and that these averages represented accurate approximations of the sulfur content of the raw feed, problems still existed in tracing the raw feed to each plant back to the bed/county combination(s) of its origin. The most important of these "tracing problem" was the exclusion of small mines from the mine ID-plant ID match file. As was discussed in Chapter 3, this problem is believed to be relatively insignificant outside of Appalachia, where small operations mine only a small percentage of the total tonnage produced. Further more, even in Appalachia (where small mine production is more significant -- See Table 3.1), this problem is not as significant as problem numbers 2 and 4 above, because the percentage of the total production effected is still not great. (Problem numbers 2 and 4 can be assumed to affect *all* production, whereas problem number 5 affects only the tonnage produced by small mines.)

6.

*Assumption that All Uncleaned Coal
Produced by Mines Served by an
Offsite Cleaning Plant Was Shipped to the Plant*

In order to trace the raw feed back to the originating bed/county combinations, it was necessary to estimate the quantity of coal received by each plant from each source mine. To quote from Chapter 3, these estimates were developed using the following procedure:

- If a given plant reported that all of the tonnage it shipped was mechanically cleaned, then the quantity of coal shipped to the plant by each mine served by the plant was set equal to the quantity of raw coal that each mine reported as having been mechanically cleaned.
- If a given plant reported that some of the coal it shipped was crushed and screened only, and/or shipped without preparation, it was assumed that the as-shipped sulfur content reported by the plant represented an average of the sulfur contents of the coal that was mechanically cleaned, the coal that was merely crushed and screened, and the coal that was shipped without preparation. Thus, to ensure that our estimate of the raw sulfur input to the plant corresponded to the same material as the reported as-shipped sulfur content, the quantity of coal shipped to the plant by each mine was set equal to the sum of the quantity of coal reported by the mine as having been mechanically cleaned (on a raw tonnage basis), the

quantity reported as crushed and screened, and/or the quantity reported as shipped without preparation.

The estimation procedure described in the second bullet item above involves the implicit assumption that none of the uncleaned coal produced by mines served by offsite cleaning plants shipping uncleaned coal was shipped directly from the mines to the consumer. Although this assumption represents a source of potential errors, its contribution to the overall uncertainty surrounding the current SO₂ reduction estimates was judged to be relatively small, because few offsite plants are shipping uncleaned coal.

7.

*Estimation of the Total SO₂ Reduction
by All Cleaning Plants Based on the
SO₂ Reduction for a Sample of Plants*

All six of the problems discussed above were caused by the lack of data on the sulfur content of the raw feed, and the concomitant need to use bed/county averages as substitutes for the missing data. One additional data-related problem that did not stem from the lack of quality data on the raw feed was identified: the use of a sample of cleaning plants to derive total SO₂ reduction estimates for the plant population. It will be recalled (from Chapter 3) that various data problems necessitated the exclusion of some plants from consideration; it was assumed that the remaining plants are representative of the total plant population. For almost all states, the sample size is large relative to the plant population (see Table 3.2); therefore, the range of potential errors resulting from our reliance on a sample of plants was judged to be fairly narrow, and, furthermore, the use of a sample was judged to be a less significant source of errors than some of the more important problems discussed previously. However, one exception to these general judgments was made for Virginia. The sample size for Virginia was small (3 plants out of a total population of 27); hence, the reliance on a sample of plants is more problematic for this state.

Uncertainty Analysis

A judgment was made as to the range of uncertainty contributed by each of the problems identified above, as per the procedure described at the beginning of this appendix. The uncertainty ranges assigned to the problems were as follows:

Problem Number	Uncertainty Range (Percent)
1	+/- 30
2	+/- 40
3	+/- 40
4	-60, +20
5 (Appalachian states)	+/- 10
5 (states outside Appalachia)	+/- 2
6	+8, -2
7 (Virginia)	+/-30
7 (all other states)	+/- 8

Next, every problem was assigned a set of scale values indicating its significance relative to every other problem (again as per the methodology described previously). The resulting matrix of scale values is presented in Table B-2. In this matrix, the first number assigned to each pair of problems is the weight, and the second number (i.e., the number in Table B-2 parentheses) indicates which of the two problems is most significant.

For example, in column number 1 (for problem number 1), row number 2 (for problem number 2), problem number 2 (the dominant problem) is assigned a weight of 9 relative to problem number 1.

The weights associated with each error component (problem) are shown in Table B-3. The weights were applied to the errors associated with each problem; the resulting overall errors estimated for the analysis of current SO₂ reduction are summarized in Table B-4.

Current SO₂ Reduction Estimates

The primary problem that affected the accuracy of the potential SO₂ reduction estimates was the lack of washability data for many bed/county combinations (see Chapter 1). However, there were other less significant problems as well. In the following subsections, each of the problems identified as having contributed to the uncertainty surrounding the potential SO₂ reduction estimates will be discussed. Each of these problems arose during one of the four steps involved in the potential SO₂ reduction estimation methodology (see Chapter 4); therefore the problems associated with each step have been grouped together.

Table B-2. Matrix of Pairwise Comparisons for the Problems Associated with the Current SO₂ Reduction Estimates

Problem Number	Problem Number						
	1	2	3	4	5 (IA) ^a	5 (OA) ^b	6
1							
2	9(2)						
3	9(3)	6(2)					
4	9(4)	1(4)	6(4)				
5 (IA)	5(5)	5(2)	1(3)	5(4)			
5 (OA)	3(%)	8(2)	5(3)	8(4)			
6	1(6)	8(2)	5(3)	8(4)	5(5)	2(5)	
7 (V) ^c	8(7)	2(2)	3(7)	2(4)	2(7)	8(7)	8(7)
7 (OS) ^d	4(7)	6(2)	2(3)	6(4)	3(5)	4(7)	4(7)

^aIA = Inside Appalachia

^bOA = Outside Appalachia

^cV = Virginia

^dOS = All states other than Virginia

Table B-3. Weights for the Problems Associated with the Current SO₂ Reduction Estimates

Problem Number	Inside Appalachia Virginia	Weight	
		Inside Appalachia Other	Outside Appalachia
1	.022	.022	0.23
2	.307	.340	.353
3	.087	.101	.124
4	.307	.340	.353
5	.082	.102	.039
6	.024	.023	.029
7	.171	.071	.081

Step 1 Problems

Three major problems associated with step 1 (development and application of the coal preparation model) were identified as follows:

1. Extension of Size Distributions from Samples with Size Distribution Data to Samples Without these Data. As was discussed in Chapter 4, size distribution data were lacking for some of the DOE washability samples, and all of the USBM washability samples. Therefore it was necessary to estimate the missing size distributions had to be estimated for a fairly large percentage of the washability samples, the lack of size distribution data represents a significant source of potential errors. However, the size of any errors introduced into the potential SO₂ reduction estimates as a result of this problem are believed to fairly small, since the size distribution data are used only to weight the washability results for the different size fractions (and, furthermore, for at least some samples the washability of the coal varied little by particle size).

Table B-4. Estimated Error in Current SO₂ Reduction Analysis

	Error (Percent) ^a	
	+	-
Inside Appalachia - Virginia	29	41
Inside Appalachia - Other	27	40
Outside Appalachia	28	42

^aThe current SO₂ reduction estimates to which these percentages apply are presented in Chapter 5, Table 5.1.

2. Estimation of Heat Content Yields for USBM Washability Data. The reader will recall (see Chapter 4) that data on the heat content of the raw and float coal was lacking for the USBM samples. As a result it was necessary to develop heat content yield estimates for the USBM samples, by assuming that the heat content of each sample, measured on an ash-free basis, remains constant over different size fractions and specific gravities of separation. This assumption was tested; the test results indicated that, after a correction is applied for a small bias, any remaining errors in the estimated yields are very small (see Table 4.3). At this point it should be added that these errors effected only the USBM washability data; these data constituted a relatively small portion of the total washability data base. hence, the use of estimated as opposed to actual heat content yields for the USBM data represents a relatively insignificant problem.

3. Use of Approximate as Opposed to Actual Partition Curves. The Skea and Rubin model makes a number of simplifying assumptions in its representation of the partition curves used to define the imperfection associated with commercial cleaning equipment. In addition to assuming that the probable error associated with each equipment type remains constant for all specific gravities of separation,* the model assumes that the partition curve for each type of equipment is linear. This second assumption is particularly significant, because it cuts off the "tails" of the partition curves. This will tend to bias the potential SO₂ reduction estimates slightly towards the high side. Although the biases introduced into the estimates as a result of the model's simplifying assumptions should not have been great, they were pervasive -- every SO₂ reduction estimates for every washability sample was effected by the simplifying assumptions.

Step 2 Problems

In step 2, each reserve block was assigned a coal type. Although the number of coal quality analyses used to develop these reserve assignments exceeded, by an order of magnitude, the number of washability samples used to assign reserve blocks in step 3, the same basic problem that arose in the third step -- namely, a lack of data for large portions of the reserves--also manifested itself to a lesser degree in the second step. Coal quality data, like washability data, were sometimes lacking at the bed/county, county, and even bed/region level. This general problem is reflected in a number of the specific step 2 problems identified as having contributed to the uncertainty of the potential SO₂ reduction estimates. These problems will be discussed below, but first it must be emphasized that although some of the step 2 problems may have led to significant errors in the characterization of the reserve base by raw coal quality, it is unlikely that any of these problems had a major impact on the potential SO₂ reduction estimates. This conclusion is based on the fact that the raw heat and sulfur content values assigned to the different reserve blocks are used only as weighting factors in the development of the potential SO₂ reduction estimates. This conclusion is based on the fact that the raw heat and sulfur content values assigned to the different reserve blocks are used only as weighting factors in the development of the potential SO₂ reduction estimates (see the equation for $F_{s,g,h,i,j}$ in Chapter 4). Therefore none of the step 2 problems described below were judged to be significant relative to the step 1 problems discussed above or the step 3 problems covered in the next subsection.

* The probable errors associated with cleaning equipment reflect the slopes of the partition curves; these slope *do* vary for different specific gravities of separation.

The problems that arose in step 2 were as follows:

1. Inclusion of Quality Analyses for Face and Channel Samples in the EIA/USBM Analytical File. The reader may recall that this problem arose during the development of the current SO₂ reduction estimates as well as during the development of the potential reduction estimates. The reader is referred to the preceding section on the current reduction estimates for a discussion of the problem.

2. Extension of Raw Coal Quality Measurements from Single Point to All the Coal Contained in the Point's Area of Influence. Again, this problem arose during the development of the current as well as the potential SO₂ reduction estimates (see problem number 2 in the preceding section on the current reduction estimates). However, in this case the areas of influence sometimes encompassed coal from beds and/or counties other than the bed and county in which the sampling point was located. Since the size of the errors resulting from this problem can be expected to have increased as the level of aggregation at which the reserve assignments were expected to have increased as the level of aggregation at which the reserve assignments were developed increased (i.e., as the areas of influence were extended beyond the beds and counties containing the sampling points), separate uncertainty ranges were developed for each of the following four levels of aggregation:

- bed/county
- county
- bed/region
- region

These separate uncertainty ranges were combined into a single range by weighting them according to the percentages of each state's reserves assigned at each level of aggregation (these percentages are provided in Table 4.12 of the main text). Thus, the overall uncertainty range assigned to this problem was relatively narrow for states in which the majority of the reserves was assigned to coal types at the bed/county level, and relatively wide for states in which the reserve assignments were developed primarily at the county and/or bed/region levels.

3. Assumption that Areas of Influence Are Equal (And Seam Thickness is Constant) Within Each Bed/County, County, Bed/Region, or Region. This problem corresponds with problem number 3 in the preceding section on the current SO₂ reduction estimates. However, as was the case for problem number 2 directly above, the degree of uncertainty associated with this problem varied depending on the level of aggregation at which the reserve assignments were developed. Therefore, separate uncertainty ranges were once again developed for each of the four levels of aggregation; these four ranges were combined into a single overall range for each state using the reserve assignment percentages in Table 4.12.

Step 3 Problems

The primary problem affecting the potential SO₂ reduction estimates -- namely, the lack of washability data for a large portion of the reserves -- manifested itself in the specific step 3

problems described below. Therefore, these problems were judged to be highly significant relative to the other (i.e., step 1, 2 and 4) problems. The specific problems were as follows:

1. Extension of SO₂ Reduction Estimates from Single Point to All the Coal Contained in the Point's Area of Influence. This problem is essentially the same as problem number 2 in the preceding subsection on step 2 problems, except in this case the number of sampling points was much smaller, due to the small size of the washability data base relative to the coal quality data base. Since the number of sampling points was much smaller, the areas of influence were much larger. Hence, while the same basic approach of specifying four separate uncertainty ranges for the four levels of aggregation was used once again, the ranges specified at each level were wider for this problem than for the step 2 problem. Again, the separate ranges were combined into a single range of uncertainty for each state by weighting them according to the percentage of the state's reserves assigned at each level of aggregation. These reserve assignment percentages are presented in Table 4.13.

2. Assumption that Areas of Influence Are Equal (And Seam Thickness Is Constant) Within Each Bed/County, County, Bed/Region, or Region. This problem corresponds to problem number 3 in the preceding subsection on step 2 problem, and it was handled in the same manner as its step 2 counterpart -- namely, by specifying separate uncertainty ranges for each of the four levels of aggregation, and combining these ranges into a single overall uncertainty range using the reserve assignment percentages (see Table 4.13) as weighting factors. The ranges specified for this problem were wider than those specified for the step 2 problem, because (as was discussed above) the areas of influence for step 3 were much larger than those for step 2.

Step 4 Problems

In step 4, the results were aggregated to the state level for both the cleaned and uncleaned portions of the 1983 production. The problems that arose during this step were as follows:

1. Use of Midpoints Rather than Actual Average Heat and Sulfur Contents for the Reserve Blocks. The reader will recall that the heat and sulfur content values assigned to each reserve block are used as weighting factors in the development of the state-level SO₂ reduction estimates. However, rather than using the actual average heat and sulfur content values for the blocks, the midpoints of the heat and sulfur content categories (see Tables 4.10 and 4.11) were used (see Chapter 4). Although the use of midpoints as opposed to actual averages represents a potential Source of errors, it must be kept in mind that the heat and sulfur content values are used only as weighting factors in the development of the potential SO₂ reduction estimates (see Chapter 4, especially the equation for $F_{s,g,h,i,j}$). Therefore, like the step 2 problem, this problem was judged to be relatively significant.

2. Use of Average SO₂ Reduction Potential Estimates for Bed/County Reserves as Approximations of SO₂ Reduction Potential Estimates for Bed/County Production. In aggregating the results to the state level, the SO₂ reduction potential estimates representative of *all* the reserves in each bed/county combination were applied to *that portion* of the reserves that was mined in 1983. Since the amenability of coal to SO₂ reduction through cleaning can vary significantly even within the same bed/county combination, this represents a significant potential source of errors. Furthermore, because operators may tend to mine that portion of the reserves that is most amenable to SO₂ reduction through cleaning prior to mining the coal that is less

responsive to cleaning, the use of overall SO₂ reduction estimates representative of the total reserves as approximations of the corresponding values for, production may have biased the state level results. However, any biases that may have been introduced into the potential SO₂ reduction estimates as a result of this problem should have been small, for two reasons. First, the washability samples used to develop the SO₂ reduction estimates were themselves obtained, mostly during the seventies, from operating mines; therefore the potential SO₂ reduction estimates developed for the reserves may in fact be more representative of current or recent production than the overall reserve base. And second, the washability of the coal is only one of the many factors an operator considers in deciding which reserves should be developed first; in fact, it is probably one of the less important factors.

Uncertainty Analysis

A judgment was made regarding the range of uncertainty contributed by each of the problems identified above; the uncertainty ranges assigned to the problems were as follows:

Problem Number*	Uncertainty Range (Percent)
11	+/- 5
12	+/- 1
13	-10, +2
21	+/- 10
22 (bed/county)	+/- 10
22 (county)	+/- 15
22 (bed/region)	+/- 15
22 (region)	+/- 25
23 (bed/county)	+/- 10
23 (county)	+/- 15
23 (bed/region)	+/- 25
23 (region)	+/- 25
31 (bed/county)	+/- 20
31 (county)	+/- 30
31 (bed/region)	+/- 30
31 (region)	+/- 40
32 (bed/county)	+/- 20
32 (county)	+/- 30
32 (bed/region)	+/- 30
32 (region)	+/- 40
41	+/- 5
42	+18, -12

*The first digit of the problem number is the number of the step in which the problem arose, and the second digit is the number used to identify the problem in the preceding discussion. For example, problem 11 corresponds to problem number 1 in the preceding subsection on step 1 problem; problem number 23 corresponds to problem number 3 in the subsection on step 2 problem, etc. The uncertainty ranges associated with each element of problem numbers 22, 23, 31, and 32 were combined into a single uncertainty range by weighting the uncertainty range by the percentage of total reserves assigned at the bed/county, county, and bed/region, and region levels.

Next, every problem was assigned a set of scale values indicating its significance relative to every other problem. The resulting matrix of scale values is presented in Table B-5. In this matrix, the first number assigned to each pair of problems is the scale value, and the second number (i.e., the number in parentheses) indicates which of the two problems is most significant. For example, in column number 11 (for problem number 11), row number 13 (for problem number 13), problem number 13 (the dominant problem) is assigned a weight of 5 relative to problem number 11.

The weights associated with each problem are shown in Table B-6. The weights were applied to the errors associated with each problem; the resulting overall errors estimated for the analysis of potential SO₂ reduction are summarized in Table B-7.

Table B-5. Matrix of Pairwise Comparisons for the Problems Associated with the Potential SO₂ Reduction Estimates

Problem Number	Problem Number									
	11	12	13	21	22	23	31	32	41	42
11										
12	3(11)									
13	5(13)	8(13)								
21	9(11)	9(12)	9(13)							
22	8(11)	5(12)	9(13)	9(22)						
23	9(11)	7(12)	9(13)	9(23)	5(22)					
31	5(31)	9(31)	1(31)	9(31)	9(31)	9(31)				
32	3(32)	7(32)	3(13)	9(32)	9(32)	9(32)	5(31)			
42	5(42)	9(42)	1(13)	9(42)	9(42)	9(42)	1(31)	5(42)	9(42)	

Table B-6. Weights for Problems Associated with the Potential SO₂ Reduction Estimates

Problem Number	Weight
11	.086
12	.047
13	.205
21	.010
22	.027
23	.017
31	.228
32	.125
41	.027
42	.228

Table B-7. Estimated Error in Potential SO₂ Reduction Analysis

State/Region	Error +	Error -
Alabama	16	17
E. Kentucky	16	16
Illinois	15	16
Indiana	15	15
Pennsylvania	21	21
Virginia	16	17
West Virginia	15	16
Western Kentucky	15	15

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